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LOW FREQUENCY ACOUSTIC DETECTION RESEARCH IN SUPPORT OF HUMAN DETECTION RANGE PREDICTION

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APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This report provides insight into aural detectability problems that apply to low frequency sound emissions from helicopters. Critical bandwidths and infrasound were researched in this study. The results provided improved Effective Masking Bandwidth data that will be incorporated into other R&D efforts at the Applied Technology Laboratory to improve aural detection prediction of Army aircraft.

Bill W. Scruggs, Jr., of the Aeronautical Systems Division served as project engineer for this effort.

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This project resulted in modifications to the ~~Applied Technology Laboratory's~~ acoustic range prediction software that were intended to increase the accuracy with which the program predicts detection ranges for targets that are audible primarily at low frequencies. These modifications were based on interpretations of the findings of a psychoacoustic experiment that sought to determine the effective masking bandwidth for human observers at frequencies as low as 40 Hz. The rationale for this experimen-

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tation was based on an extensive search of the masking literature.

The possibility that acoustic detection ranges of unaided human observers are affected by infrasonic emissions of helicopters was considered both analytically and empirically. It was concluded from a literature review that the prospects for "infrasonic cueing" of conventional acoustic detection were doubtful. A two-alternative forced choice task in which infrasound was available as a cue to detection produced results consistent with that conclusion.

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INTRODUCTION

PURPOSE OF STUDY

The Applied Technology Laboratory sponsored the current research to investigate two potential sources of error in existing software that predicts acoustic detection ranges for human observers. They are (1) the influence of infrasonic emissions of helicopters on aural detectability, and (2) uncertainty in estimates of effective masking bandwidths at low frequencies. The software described in Reference 1 does not consider the former influence. It relies on extrapolation of higher frequency masking bandwidth information to estimate low frequency masking bandwidths.

It was hypothesized that if human observers were sensitive to infrasonic emissions of helicopters, then the presence of infrasonic energy could provide a cue to aural detection that might increase helicopter detection range beyond that which would be based on conventional (non-infrasonic) acoustic energy alone. Prior to the current study, there was no reliable information on the width of the hypothetical filter with which it is convenient to model human observers' detection of signals at frequencies below about 125 Hz. If the bandwidth of this filter were wider than that used by the existing software, then, all other things being equal, predicted detection ranges would be expected to decrease.

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[1] Abrahamson, A. Louis, CORRELATION OF ACTUAL AND ANALYTICAL HELICOPTER AURAL DETECTION CRITERIA, Volume 1, Wyle Laboratories; USAAMRDL Technical Report 74-102A, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, January 1975, AD B002067.

Similarly, if the bandwidth of this filter were narrower than that used by the existing software, predicted detection ranges would be expected to increase.

ORGANIZATION OF REPORT

This report summarizes efforts undertaken in several areas to improve understanding of human signal detection at low frequencies. The Background section provides information in the form of reviews of the literature estimating low frequency effective masking bandwidths and the literature dealing with effects of infrasonic energy on human observers. Subsequent sections provide details of the method and results of a laboratory test on low frequency effective masking bandwidths, and similar information about an infrasonic study. The Discussion section considers the application of this empirical information to the Applied Technology Laboratory's existing software. Conclusions and recommendations for further refinement of that software are presented.

BACKGROUND

REVIEW OF HUMAN MASKING BANDWIDTH RESEARCH

A basic fact about research on masking frequency bands affecting human acoustic detection performance is that there are large differences among available bandwidth estimates. Some of these differences are due to conflicting concepts of what a "critical" band is, and some are due to different psychophysical measurement techniques. Since the main purpose of this project is to refine the means of predicting the detectability of a signal heard in the presence of masking noise, the review will focus on masking bandwidths estimated in detection-related studies, even though other estimates and procedures are also discussed. An historical approach is taken to provide a background of understanding.

History

Quantitative studies of the ear's ability to perform frequency analyses were started in the 1920's when electronics first made precise control of acoustic signal parameters (especially intensity) possible. Considerable interest and speculation about psychoacoustic phenomena preceded the initial quantitative studies, however. Ohm's Acoustic Law (Reference 2) is a statement that the ear can "break up" a complex periodic waveform and discriminate individual components of the complex. Helmholtz (Reference 3) used Ohm's principle in a place-resonance

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[2] Ohm, G. S., ÜBER DIE DEFINITION DES TONES, NEBST DARAN GEKNÜPFTER THEORIE DER SIRENE UND ÄHNLICHER TONBILDENDER VORRICHTUNGEN, Annalen der Physik und Chemie, 59, 513-565, 1843.

[3] Helmholtz, H.L.F., DIE LEHRE VON DEN TONEMPFINDUNGEN ALS PHYSIOLOGISCHE GRUNDLAGE FUR DIE THEORIE DER MUSIK, 1st Edition, Brunswick, Germany, Viewegverlag, 1863.

theory of hearing, suggesting that the hearing organ acted as a resonance device such that different places along the receptor surface were differentially responsive to different frequencies. Wegel and Lane (Reference 4) were the first to study how one sound (a sinusoid) could make another sound (another sinusoid) difficult or impossible to hear. Studies of this sort are called masking studies: the "signal" is the sound one is trying to hear, while the sound obscuring or trying to obscure the signal is called the "masker". A series of similar studies ensued. Fletcher (Reference 5) used noise as a masker and varied the bandwidth of the noise about a signal (a sinusoid) centered in the middle of the band. He concluded that, functionally, one could treat the ear as a narrow filter, and published estimates of the width of that filter as a function of its center frequency. Fletcher was among the first to call this hypothesized filter a "critical band". Schafer, Gales, Shewmaker and Thompson (Reference 6) further explored and confirmed Fletcher's research as did Swets, Green and Tanner (Reference 7).

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[4] Wegel, R. L., and C. E. Lane, THE AUDITORY MASKING OF ONE PURE TONE BY ANOTHER AND ITS PROBABLE RELATION TO THE DYNAMICS OF THE INNER EAR, Physical Review, 23(2), 266-285, 1924.

[5] Fletcher, H., AUDITORY PATTERNS, Review of Modern Physics, 12, 47-65, 1940.

[6] Schafer, T. H., Gales, R. S., Shewmaker, C. A., and Thompson, P. O., THE FREQUENCY SELECTIVITY OF THE EAR AS DETERMINED BY MASKING EXPERIMENTS, Journal of the Acoustical Society of America 22, 490-496, 1950.

[7] Swets, J. A., Green, D. M., and Tanner, W. P., Jr., ON THE WIDTH OF CRITICAL BANDS, Journal of the Acoustical Society of America 34, 108-113, 1962.

In 1957 Zwicker, Flottorp and Stevens (Reference 8) published an important paper. Their main area of interest was loudness summation rather than detectability, but they reviewed a number of studies, mainly those by Zwicker and Feldtkeller (Reference 9), Gassler (Reference 10), and Zwicker (References 11 and 12). They published a list of bandwidths as a function of frequencies called "Frequenzgruppen" after the German designation. These frequenzgruppen or critical bands are a factor of two to three times wider than Fletcher's estimates. Table 1 compares the estimates. Notice that at lower frequencies the discrepancies in the estimates of bandwidth are somewhat smaller than at higher frequencies. Nevertheless, there are still sizeable discrepancies even at low frequencies.

One should also appreciate that any single method of estimating critical bandwidths will show some variability. For example, at 1000 Hz, Fletcher (Reference 5) estimates 60 Hz;

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[8] Zwicker, E., Flottorp, G., and Stevens, S. S., CRITICAL BAND WIDTH IN LOUDNESS SUMMATIONS, Journal of the Acoustical Society of America 29, 548-557, 1957.

[9] Zwicker, E., and Feldtkeller, R., ÜBER DIE LAUTSTÄRKE VON GLEICHFORMIGEN GERÄUSCHEN, Acustica 5, 303, 316, 1955.

[10] Gassler, G., ÜBER DIE HÖRSCHWELLE FÜR SCHALLEREIGNISSE MIT VERSCHIEDEN BREITEM FREQUENZSPEKTRUM, Acustica 4, Akustische Beiheft 1, 408-414, 1954.

[11] Zwicker, E., DIE VERDECKUNG VON SCHMALBANDERÄUSCHEN DURCH SINUSTÖNE, Acustica 4, Akustische Beiheft 1, 415-420, 1954.

[12] Zwicker, E., DIE GRENZEN DER HÖRBARKEIT DER AMPLITUDEN-MODULATION UND DER FREQUENZMODULATION EINES TONES, Acustica 2, Akustische Beiheft 3, 125-133, 1952.

TABLE 1. CRITICAL BAND ESTIMATES

Center Frequency	Fletcher's Critical Band*	Frequenzgruppen**
50		80
100	87	
150		100
200	52	
250		100
315	50	
350		100
400	50	
450		110
570		120
630	53	
700		140
800	58	
840		150
1000	63	160
1170		190
1250	71	
1370		210
1400	76	
1600	83	240
1800	98	
1850		280
2000	98	
2150		320
2500	123	380

*Appendix from American National Standard Methods for Measurement of Sound Pressure Level S1.13-1971.

**Zwicker, E., SUBDIVISION OF AUDIBLE FREQUENCY RANGE IN CRITICAL BANDS (FREQUENZGRUPPEN), Journal of the Acoustical Society of America 33, p. 248 (1961).

TABLE 1 (Continued)

Center Frequency	Fletcher's Critical Band	Frequenzgruppen
2900		
		450
3150	150	
3400		
		550
4000	204	
		700
4800		
		900
5800		
		1100
6300	404	
7000		
		1300
8000	589	
8500		
		1800
10000	832	
		2500
10500		
		10500

Schafer et al. (Reference 6), 65 Hz; Swets et al. (Reference 7), (half power of Gaussian filter) 80 Hz; Patterson (Reference 13), 59 Hz; and so forth. All of these values are distinctly different from Zwicker's estimate of 160 Hz. It is clearly a phenomenon other than experimental error that leads to the diverse estimates.

One must simply recognize that there are two sets of estimates - the German and the American. One generalization is that the American estimates are strongly influenced by masking data, in particular, the detectability of a sinusoid in noise, whereas the German estimates are more strongly influenced by estimates from loudness summation, phase effects, and similar experiments. Even this generalization does not completely explain the difference since Gassler (Reference 10) measured the detectability of tone complexes of various spacing in a masking noise and obtained estimates of bandwidth very similar to frequenzgruppen values. However, Spiegel (Reference 14) has repeated Gassler's study and obtained estimates nearer Fletcher's value. Similarly, Zwicker (Reference 11) and Green (Reference 15) disagree about the apparent bandwidth obtained with two tones as a masker.

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[13] Patterson, R. D., AUDITORY FILTER SHAPE, Journal of the Acoustical Society of America 55, 802-809, 1974.

[14] Spiegel, Murray F., LIMITS OF SPECTRAL INTEGRATION: AN INVESTIGATION OF THE DETECTABILITY OF AUDITORY NARROW AND WIDE BAND SIGNALS, Doctoral Dissertation, Washington University, St. Louis, Missouri, 1978.

[15] Green, D. M., MASKING WITH TWO TONES, Journal of the Acoustical Society of America 37, 802-813, 1965.

Techniques Used to Measure Critical Band

Band-narrowing experiment. Fletcher's procedures may be taken as a prototype of this approach. The bandwidth of Fletcher's noise masker was the independent variable of the experiment. The signal, a sinusoid, was located in the center of the band of noise for all conditions of the experiment. Fletcher started by measuring the threshold energy for the signal in wideband noise of some constant noise-power density, N_0. Thus, the first data point in the experiment was the threshold value of the signal when the masker was a wideband noise.

The next condition of Fletcher's experiment was to decrease the bandwidth of the noise, holding the noise-power density constant, to determine if the change in bandwidth had any influence on the threshold for the signal. If the threshold of the signal remained unchanged, it could be inferred that the noise masker energy attenuated by the filtering operation was ineffective in masking. If, on the other hand, the threshold of the signal was lowered and the signal became easier to hear, it could be inferred that the attenuated energy was effective in masking.

The width of the noise masker at which the signal first began to become easier to hear was taken as the measure of the width of an internal auditory filter. The point at which the signal becomes 3 dB easier to hear may be arbitrarily selected as the effective width of the filter. According to Fletcher's data, the effective width of the filter is about 60 Hz around a signal frequency of 1,000 Hz. Fletcher called this bandwidth at which the signal becomes easier to hear the *critical band*.

It should be noted that throughout the experiment the noise-power density, N_0, (the noise level in a 1 Hz band near the signal frequency) is held constant. Thus, as the bandwidth of the noise is reduced, the total power of the noise is also reduced. In fact, the change in noise bandwidth from roughly 10,000 Hz to 90 Hz reduces the noise power by more than 20 dB. Such a reduction in power produces a dramatic decrease in the loudness of the noise, but the threshold level of the signal remains nearly unchanged. Were the bandwidth to be held constant and the noise power density changed by 20 dB, the threshold for the signal would also be changed 20 dB.

Variants of this technique include the experiment by Schafer et al. (Reference 6), which used a notch in a noise of varying width as an independent variable. As the width of the notch was increased, a sinusoid located in the center of the notch became easier to hear. Swets et al. (Reference 7) used more detailed assumptions concerning the shape of the filter and obtained, as an estimate, the bandwidth that minimized the fit to the obtained data. Unfortunately, the minimum was found to be fairly broad and hence the bandwidth estimates were not particularly precise. Bos and deBoer (Reference 16) used both Fletcher's band-narrowing procedure and a discriminated increment in a noise band. Patterson (References 13 and 17) used a variant of Fletcher's band-narrowing technique and attempted to determine the entire filter shape. His bandwidth estimates were remarkably close to Fletcher's - 70 Hz at 1000 Hz, 100 Hz at 2000 Hz, and 200 Hz at a center frequency of 4000 Hz.

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[16]Bos, C. E., and deBoer, E., MASKING AND DISCRIMINATION, Journal of the Acoustical Society of America 39, 708-715, 1966.

[17]Patterson, R. D., AUDITORY FILTER SHAPES DERIVED WITH NOISE STIMULI, Journal of the Acoustical Society of America 59, 640-654, 1976.

Zwicker (Reference 11) and Green (Reference 15) used two tones as a masker and located a signal midway between them. As the two maskers were separated in frequency, the signal became easier to hear. The two sinusoidal maskers beat at narrow separations and hence made estimates of bandwidth difficult. In addition, Zwicker's and Green's data show large discrepancies, the explanation for which remains unclear.

Greenwood (Reference 18) used a band of noise with very sharp skirts and measured the threshold of a pure tone at various frequencies above, below, and in the band of noise. For very narrow bands the masking curve relating signal threshold to signal frequency was found to be an inverted V-shaped function with a peak near the center frequency of the noise band. For wider bands of noise the function became trapezoidal, with a flat top in the region of the noise band and lower thresholds at remote frequencies. Figure 1 shows some typical data of this sort. In this example, a trapezoidal function is observed; hence, the masking noise bandwidth (720 Hz) is greater than a critical bandwidth at the signal frequencies being tested. Greenwood noted that the noise bandwidth that caused a break from the inverted V shape to the trapezoidal form occurred at a frequency approximately equal to the frequenzgruppen. Patterson, using a filter width approximating that given by Fletcher's estimates, manages to account for most of Greenwood's data. Figure 1 shows Patterson's theory and Greenwood's data points.

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[18] Greenwood, D. D., AUDITORY MASKING AND THE CRITICAL BAND, Journal of the Acoustical Society of America 33, 484-502, 1961.

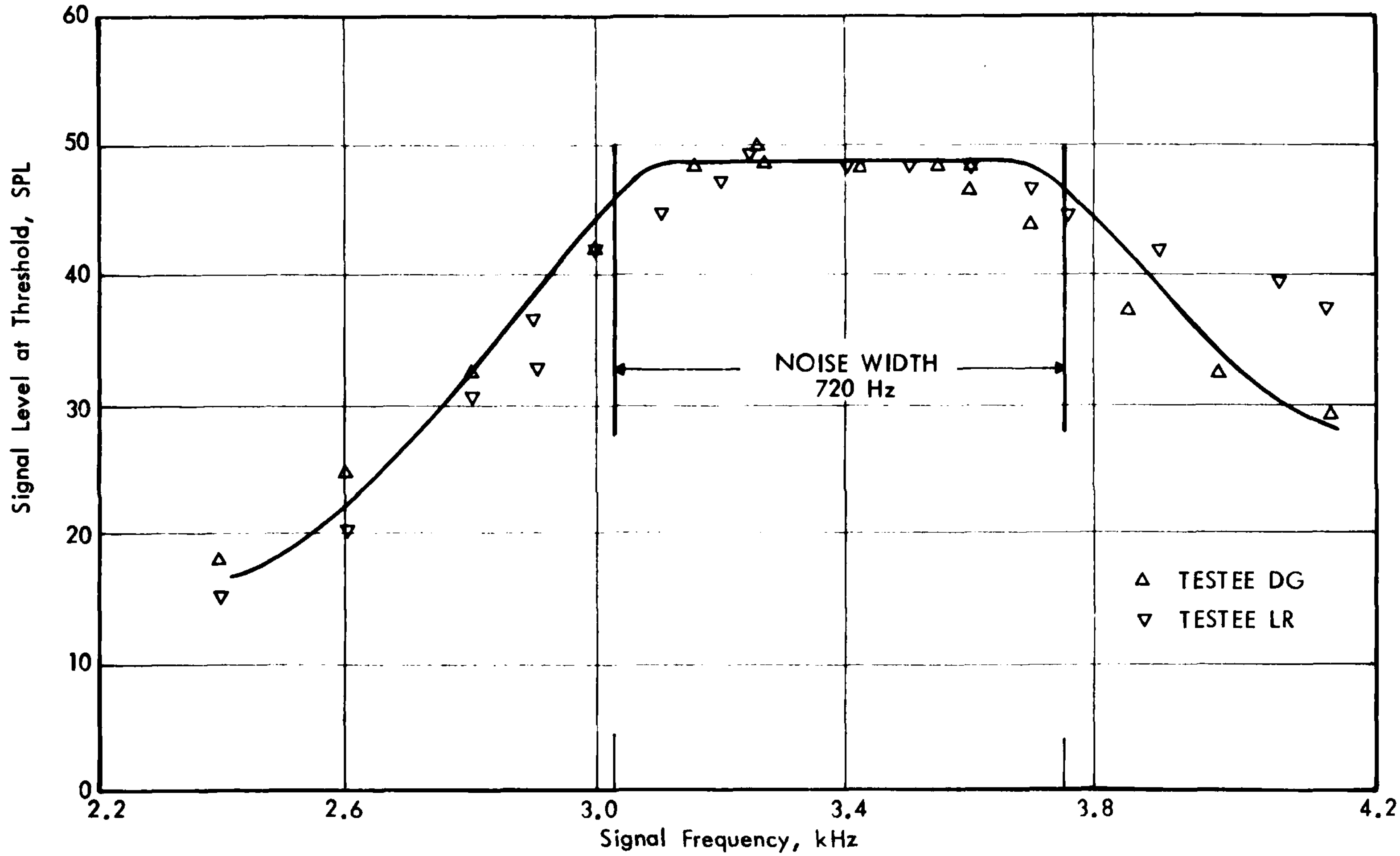

Figure 1. Patterson's Theoretical Account of Greenwood's Data, Using Fletcher's Bandwidth Estimates.

Critical ratio method. In his original investigation, Fletcher (Reference 19) noted the following empirical rule: for wide-band noise conditions the product of the critical bandwidth and the noise-power density (i.e., the total noise power at the output of an assumed auditory filter) was nearly equal to the signal power at threshold. In symbols,

$$S_t = W_c N_o \qquad \text{for } W > W_c, \tag{1}$$

where N_o is the noise-power density, S_t is the threshold power for the signal, W_c the critical band, and W the bandwidth of the noise. If the noise bandwidth is less than a critical band, a threshold signal level would simply vary as the product of the noise band and the noise-power density as follows:

$$S_t = WN_o, \qquad W \leq W_c. \tag{2}$$

If this generalization were true, then one could calculate the critical band quite simply from any data gathered in a wide-band masking condition. Since both N_o and S can be measured at threshold, a critical bandwidth (W_c) can be estimated from Equation (1). Since the estimate is obtained from the ratio of S_t divided by N_o, it is called a "critical ratio" estimate. In fact, many of the "critical band" estimates obtained from Fletcher's book (Reference 19) are undoubtedly based on such a method.

Such estimates are certainly arbitrary, as Zwicker, Flottorp, and Stevens (Reference 8) have observed. It is also important to remember that the duration of the signal plays a role in

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[19] Fletcher, H., SPEECH AND HEARING IN COMMUNICATION, New York, Van Nostrand, 1953.

the estimated signal threshold. Fletcher (Reference 5) used a continuous signal, as did Hawkins and Stevens (Reference 20) in their later study. Using a 0.1-sec signal, however, Green, McKey, and Licklider (Reference 21) obtained results similar in shape to the older studies. Despite their use of an unlimited signal duration, Hawkins and Stevens obtained about the same threshold as Green and his colleagues. This is probably because Hawkins and Stevens asked the subject to adjust the signal level until it had a definite pitch rather than until it was just audible.

Phase experiments. One can construct a three-component complex signal by amplitude modulating a carrier frequency. For amplitude modulation the carrier and two side bands are all in the same phase. If one uses frequency modulation and the ratio of the range to rate of modulation is sufficiently small, then side bands beyond the first are negligible. In this case, to a first approximation, AM and FM modulation differ in that the phase of one of the side bands is reversed. A third, three-component signal can be generated by taking an AM complex and changing (delaying) the phase of the carrier by 90°. The latter stimulus is called quasi-frequency modulation (QFM). Zwicker (Reference 12) compared an observer's ability to hear the difference between AM and FM signals. Goldstein (Reference 22) compared observers' ability to hear the differences between

[20] Hawkins, J. E., Jr., and Stevens, S. S., THE MASKING OF PURE TONES AND OF SPEECH BY WHITE NOISE, Journal of the Acoustical Society of America 22, 6-13, 1950.

[21] Green, D., McKey, M., and Licklider, J. C. R., DETECTION OF A PULSED SINUSOID IN NOISE AS A FUNCTION OF FREQUENCY, Journal of the Acoustical Society of America 31, 1446-1452, 1959.

[22] Goldstein, J. L., AUDITORY SPECTRAL FILTERING AND MONAURAL PHASE PERCEPTION, Journal of the Acoustical Society of America 41, 458-479, 1967.

QFM and AM signals. The results were similar: when all three components are close together, it is easy to discriminate between the pairs - phase is no longer audible. The spacing between the side band components at which discrimination fails is an estimate of another kind of critical band and this critical bandwidth follows the frequenzgruppen numbers very closely in both Zwicker's and Goldstein's study. Similar earlier results were obtained by Mathes and Miller (Reference 23).

Change in loudness of multitone complexes. Zwicker and Feldtkeller (Reference 9) were the first to pursue this procedure but many replications by Zwicker et al. (Reference 9), by Scharf (References 24 and 25), and by Bauch (Reference 26) have confirmed the basic facts. Consider a four-tone complex with each component of the complex spaced equally in frequency from each other about some center frequency. The observer listens to the complex and adjusts a noise to equal it in loudness. The frequency separation of the components is then increased and the loudness match repeated. As long as all components are less than some critical value the loudness of the

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[23] Mathes, R. C., and Miller, R. L., PHASE EFFECTS IN MONAURAL PHASE PERCEPTION, Journal of the Acoustical Society of America 19, 780-797, 1947.

[24] Scharf, B., CRITICAL BANDS AND THE LOUDNESS OF COMPLEX SOUNDS NEAR THRESHOLDS, Journal of the Acoustical Society of America 31, 365-370, 1959.

[25] Scharf, B., LOUDNESS SUMMATION UNDER MASKING, Journal of the Acoustical Society of America 33, 503-511, 1961.

[26] Bauch, H., DIE BEDEUTUNG DER FREQUENZGRUPPE FÜR DIE LAUTHEIT VON KLANGEN, Acustica 6, 40-45, 1956.

complex is the same. As the components begin to fall outside some critical range of frequencies the loudness increases (at least at moderate and high levels, e.g., 30-40 dB above threshold). This breakpoint corresponds very closely to the frequenzgruppen values.

<u>Critical band estimates at low frequencies</u>. Figure 2 presents a graph relating estimates of the critical bandwidth as a function of frequency for three studies using the critical ratio method. These are the studies most directly pertinent to current interest because the basic data of these studies is simple - it is the signal level at which a sinusoidal signal is audible in a white noise background. In fact the left ordinate shows the ratio of signal level to noise-power density at each signal frequency. This graph is also representative of most studies of the critical band in that there are many more estimates above 1000 Hz than below it.

Table 2 presents a summary of all data available for frequencies <u>below</u> 1000 Hz for all methods. At any frequency, detection or masking experiments tend to give lower estimates of bandwidth than do loudness experiments with the phase results yielding intermediate estimates. The phase results are interesting in that they suggest that the critical bandwidth decreases with center frequency (down to 64 Hz) and do not support the slight increase shown in Figure 2, present in the analyses of both Fletcher (Reference 19) and Hawkins and Stevens (Reference 20). Table 2 indicates that there is insufficient data at low frequencies to make any strong inference about how bandwidth changes at those frequencies. The only extensive data below 500 Hz is that shown in Figure 2, using the critical ratio method.

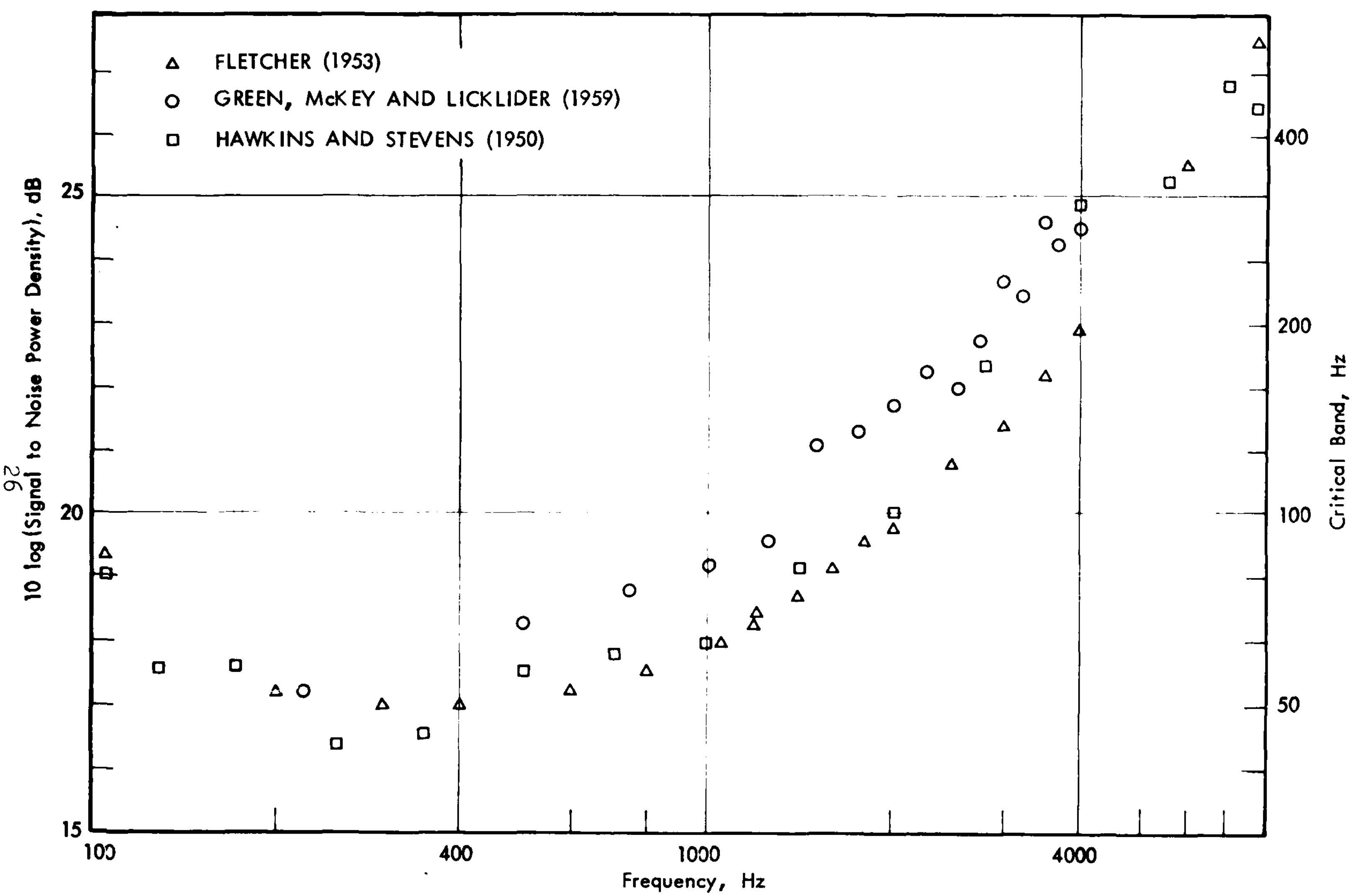

Figure 2. Critical Ratio Estimates of Effective Masking Bandwidths as a Function of Frequency.

TABLE 2. CRITICAL BAND ESTIMATES BELOW 1000 HZ

INVESTIGATOR	TECHNIQUE	CENTER FREQUENCY	CRITICAL BANDWIDTH
Gässler (1954)	Detection of multiple of various Δfs	250	80
Zwicker (1954)	Two-tone masking	570	150
Zwicker and Feldtkeller (1955)	Loudness change as function of frequency	500	100 (at 70 dB) 200 (at 30 dB)
Bauch (1956)	Loudness change as function of frequency	400	80 (at 70 dB) 80 (at 45·dB)
Scharf (1959)	Loudness change as function of frequency	500	100
Zwicker (1952)	Phase effects	500 250 120 60	120 86 72 64
Goldstein (1967)		250	100
Greenwood (1961)	Masking	480	104
Schafer et al. (1950)	Masking	200	65
Patterson (1976)	Masking	500	69
Bos and deBoer (1966)	Masking	500	55
Hawkins and Stevens (1950)	Critical ratio	(Plotted in Figure 2)	
Fletcher (1953)	Critical ratio	(Plotted in Figure 2)	
Green, McKey, and Licklider (1959)	Critical ratio	(Plotted in Figure 2)	

The problem associated with the critical ratio method at low frequencies is that unless one is very careful to exclude external noise there is a strong likelihood that the signal threshold will be artificially high. This artificially high threshold will lead to artificially high estimates of the critical bandwidth as the left-hand ordinate of Figure 2 indicates. Spurious external noise is most likely at low frequencies, since noise radiated from machinery such as air conditioners, ventilation fans, or traffic is likely to be more of a problem at low frequencies than at high frequencies.

A second, less obvious, source of unmeasured low frequency noise arises from the vascular system of the observer. Shaw and Piercy (Reference 27) have made estimates of the magnitude of this noise from probe tube measurements in the ear canal. The spectrum of this noise falls rapidly as a function of frequency. The 1/3 octave level is 70 dB SPL at 16 Hz, 34 dB at 125 Hz, and 12 dB at 250 Hz. These levels will be about 14 dB higher with earphone listening, as is true of all studies shown in Figure 2.

It is already known that this spurious low frequency noise can profoundly influence psychoacoustic results. For some years a binaural phenomenon known as the masking level difference (MLD) has been studied as a function of frequency and has shown anomalous results. The masking level difference is the improvement in the detectability of a sinusoidal signal when presented 180° out of phase at the two ears compared with the 0° phase condition, where the masking noise is constant in

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[27] Shaw, E. A. G., and Piercy, J. E., PHYSIOLOGICAL NOISE IN RELATION TO AUDIOMETRY, Journal of the Acoustical Society of America 34, 754(A), 1962.

both ears. The size of the MLD is about 15 dB at 500 Hz. Initial data (Reference 28) showed a decrease in the size of the MLD at lower frequencies.

Dolan (Reference 29) showed that this decrease in the size of the MLD with frequency did not occur at very high noise levels (above a spectrum level of 50 dB). Presumably these high noise levels overrode any residual room or ear-channel noise (which would tend to be uncorrelated in the two ears) and thus preserved the binaural advantage for the low frequency signals.

Green et al. (Reference 21) used a single spectrum level of 45 dB. Fletcher's estimates were taken from a variety of data, largely unspecified but presumably including several different noise levels. Hawkins and Stevens used more spectrum levels ranging from -10 dB to 60 dB in 10 dB steps.

Literature Summary

1. Estimates of critical bandwidths, critical ratios, and similar quantities are very sensitive to their manner of measurement.

2. Two distinct sets of estimates are distinguishable, varying by a factor of about three or more at low frequencies.

3. Those estimates produced by techniques most similar to the task at hand (detection of helicopter noise signatures), i.e., the "American" estimates, appear to be the more relevant.

[28] Hirsh, I. J., THE INFLUENCES OF INTERAURAL PHASE ON INTERAURAL SUMMATION AND INHIBITION, Journal of the Acoustical Society of America 20, 536-544, 1948.

[29] Dolan, T. R., EFFECT OF MASKER SPECTRUM LEVEL ON MASKING-LEVEL DIFFERENCES AT LOW SIGNAL FREQUENCIES, Journal of the Acoustical Society of America 44, 1507-1512, 1968.

4. Regardless of estimation techniques, there is very little reliable data at low frequencies.

5. Considerable care must be taken to avoid inflated estimates of low frequency masking bandwidths due to external noise.

REVIEW OF HUMAN SENSITIVITY TO INFRASOUND

Helicopters produce considerable acoustic energy at low frequencies associated with rotor passage rates. It has been suggested that people may be able to detect this energy either by conventional or unconventional means at great distances. This section considers a variety of means whereby human observers may become aware of infrasound of the sort produced by helicopters. The direct effects of infrasound on people and the possibility of detection by ordinary auditory perception, by the skin senses, and by unconventional sensory channels are discussed.

Direct Effects of Infrasound on People

Human maladies alleged to be associated with infrasonic exposure include an impressively long list of unpleasant conditions, including (in alphabetical order): allergy, annoyance, anxiety, blurred vision, brain tumors, chest pains, circulatory inhibition, choking, confusion, coughing, crib death, discomfort, disorientation, dizziness, drunkenness, fatigue, gagging, giddiness, headache, hearing damage, insanity, lung collapse, malaise, nausea, nervous breakdown, panic, paralysis, respiratory suppression, retching, salivation, threats of

suicide, upset stomach, vascular infection, and weakness (Reference 30).

It is probably reasonable to assume that prolonged, continuous exposure to extremely high levels of infrasound might eventually produce at least a few of the milder symptoms noted above. Documentation of dosage-response relationships for any of these effects is tenuous at best, however. For present purposes the levels of infrasound produced by helicopters at distances of a few hundred meters or more are so far below the levels at which the above symptoms are likely to occur that their possibility of occurrence may be ignored.

Detection of Infrasound by Conventional Hearing Mechanisms

Figure 3 shows the low frequency portion of the familiar human threshold of hearing curves (Reference 31). The extrapolated portion is in good agreement with recent data of Yeowart (Reference 32). Note that the threshold rises steeply in the frequency region in which helicopters typically produce the greatest amounts of infrasonic energy. The highest infrasonic spectrum level (level in a 1 Hz band) of a UH-1H helicopter hovering 500 meters overhead is on the order of 75 dB re 20 μ Pa, and occurs at the main rotor fundamental frequency in the

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[30] Broner, N., THE EFFECTS OF LOW FREQUENCY NOISE ON PEOPLE - A REVIEW, Journal of Sound and Vibration 58, No. 4, June 1978.

[31] ISO Recommendation R 226, NORMAL EQUAL-LOUDNESS CONTOURS FOR PURE TONES AND NORMAL THRESHOLD OF HEARING UNDER FREE FIELD LISTENING CONDITIONS, International Standards Organization, December 1961.

[32] Yeowart, N. S., THRESHOLDS OF HEARING AND LOUDNESS FOR VERY LOW FREQUENCIES, in Tempest, W., INFRASOUND AND LOW FREQUENCY VIBRATION, New York, Academic Press, 1976.

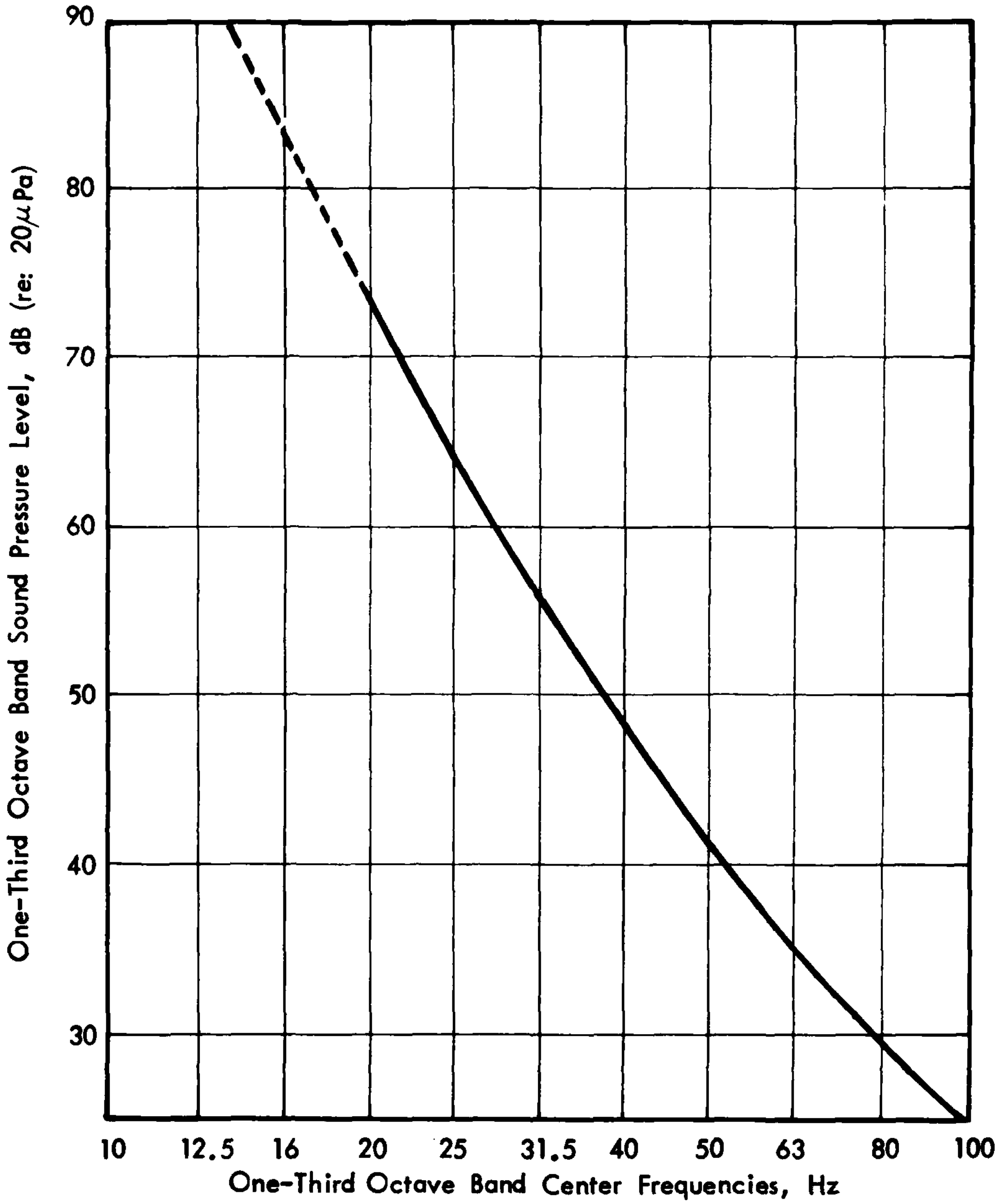

Figure 3. Approximate Threshold of Hearing at Low Frequencies Extrapolated to 10 Hz.

octave between 10 and 20 Hz.

In the same spectral region, most estimates of the human threshold of hearing are about 10 dB higher. The first and second harmonics of the main rotor have spectrum levels about 20 dB lower than the fundamental, in spectral regions (up to about 40 Hz) where the threshold of hearing is also about 20 dB lower.

Even if the unmasked threshold at infrasonic frequencies were sufficiently low, there would be reason to question the significance of infrasonic sensations. Von Bekesy (Reference 33) has noted marked discontinuities in loudness and pitch in the frequency region from about 10 Hz to 40 Hz. The stepwise form of the threshold of hearing curve has been attributed to quantal effects in neural transmission. Since most people have little experience interpreting sudden halvings or doublings in pitch and loudness as a signal changes very slightly in frequency, it is not at all clear that the eardrum's movements at very low frequencies could be interpreted.

There are enough uncertainties in figures such as those quoted above to render it difficult to assert positively that humans either can or cannot directly hear the infrasonic emissions of distant helicopters. The helicopter's infrasonic emissions have some small degree of directionality and some dependence on mode of flight, and thus may not be specified exactly; atmospheric and terrain conditions may alter propagation sufficiently to result in momentary but sizeable changes in level;

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[33] Von Bekesy, Georg, EXPERIMENTS IN HEARING, New York, McGraw-Hill, 1960.

some helicopters may produce infrasonic spectra with more pronounced harmonics than others; the sensitivity of certain individuals may be somewhat greater than the estimates of Figure 3; masking noise at some frequencies may exert a significant influence on audibility; etc. It is also conceivable that secondary emissions of resonant systems excited by low frequency energy could be detected by human observers at higher frequencies.

All things considered, the likelihood of direct audibility of a helicopter's infrasonic signature at ranges beyond a few hundred meters appears negligibly small. Furthermore, even if the infrasonic noise signature were marginally audible at some times, it would not necessarily serve as an adequate basis for a decision about the presence or absence of hostile aircraft. First, it would be extremely difficult for an unaided observer to localize the source of the infrasound. Second, the source could well be out of the line of sight, so that its range would be virtually impossible to estimate by ear alone (since the shape of the higher frequency portion of the spectrum would probably be unknown). It would thus be difficult to determine whether the infrasound was produced by one or more helicopters miles away, engaged in irrelevant operations, or whether the infrasound was produced by an approaching hostile aircraft. Third, the "alerting" value of a weak infrasonic signal would be small, since confidence in its detection would be very low (i.e., the false alarm rate would be high for a given hit rate).

Thus, although the possibility of direct audibility of infrasonic emissions of helicopters at significant ranges cannot be dismissed out of hand, it appears that direct audibility of

the infrasonic portion of a helicopter's noise signature cannot play an appreciable or reliable role in unaided acoustic detection by human observers in realistic situations. It should be remembered, however, that narrowband electroacoustic systems (such as that described by Fidell et al., Reference 34) can greatly assist human observers in detection of the infrasonic emissions of helicopters.

Detection of Infrasonic Energy by Other Sensory Systems

Although it appears that the ears can not play an important role in detection of infrasonic energy produced by helicopters at significant ranges, the possibility remains that human observers might first become aware of the presence of distant helicopters by somesthetic sensitivity.

The most likely of the skin senses to be stimulated by infrasonic radiation from helicopters is the tactile sense. As VanCott and Kinkade (Reference 35) point out, "touch sensitivity is dependent on deformation of the skin", which would require some mechanical motion to be induced by infrasonic energy. Both the rate and spatial gradient of deformation play major roles in sensitivity, since the skin differentiates pressure both in time and space, and is quite insensitive to static pressure applied over large areas.

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[34]Fidell, Sanford, Starr, Edward A., and Green, David M., FEASIBILITY OF ACOUSTIC DETECTION WITHIN ARMORED VEHICLES, U.S. Army Tank-Automotive Research and Development Command Technical Report No. 12239, January 1977.

[35]VanCott, Harold P., and Kinkade, Robert G., HUMAN ENGINEERING GUIDE TO EQUIPMENT DESIGN, New York, McGraw-Hill, 1972.

VanCott and Kinkade claim that maximum sensitivity to vibration (presumably, periodic deformation of the skin by a small or point source) occurs at about 250 Hz, a frequency an order of magnitude higher than infrasound from helicopters. Geldard (Reference 36) also presents evidence and cites earlier studies suggesting that fingertip sensitivity to punctate stimulation peaks in a band roughly an octave wide, centered at about 250 Hz.

Geldard (Reference 37) stresses that touch sensitivity varies greatly from one part of the body to another (by as much as 50 dB), and that all tactile sensation has "temporal, intensitive, and spatial aspects". Geldard also notes that familiar patterns of cutaneous sensation are named "touch, contact, tickle, vibration, dull pressure, etc.", but that other patterns of sensation "go unnamed or are indefinitely dubbed simply pressure".

Thus, the likelihood of detection of the infrasonic emissions of distant helicopters by somesthetic means would seem to be even smaller than the likelihood of direct auditory detection. First, the skin is many orders of magnitude less sensitive to airborne pressure fluctuations than the ear. Second, there is no reliable means for transduction of atmospheric infrasonic pressure fluctuations into some form of fluttering contact (as by clothing or large panels) with the skin that could serve as a basis for detection at useful ranges. Third, peak sensitivity

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[36] Geldard, F. A., THE PERCEPTION OF MECHANICAL VIBRATION. II. THE RESPONSE OF PRESSURE RECEPTORS, Journal of General Psychology 22, 271-280, 1940.

[37] Geldard, Frank A., THE HUMAN SENSES, New York, John Wiley and Sons, Inc., 1972.

of the skin senses is limited to a few parts of the body (fingers, lips, etc.), and occurs at a frequency far higher than the infrasonic portion of a helicopter's noise signature.

Perception of Objects at a Distance by Extraordinary Means

The five conventional human senses (sight, hearing, taste, smell, and proprioception) are sensitive to electromagnetic, mechanical, and chemical stimulation. Speculation about the existence of other human sensory systems (and indeed, about extrasensory systems) has been an engaging pastime since antiquity. The nature of this speculation of present interest has been most often discussed under the rubric of "facial vision", especially in connection with the ability of the blind to detect obstacles at a distance. It is easily demonstrated that facial vision is in fact of no relevance to the current problem of detection of helicopters at great distances by infrasonic emissions.

Supa et al. (Reference 38) trace serious interest in the possibility of facial vision to Diderot, who in 1749 commented on a supposed "amazing ability" of a blind person to detect the presence of objects and estimate their distance. Throughout the nineteenth century, this topic attracted continuing philosophical and experimental attention. By the end of the nineteenth century, a wide variety of hypotheses had been advanced to account for the phenomenon, ranging from the belief that the entire process was mediated by ordinary auditory perception of a number of occult explanations.

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[38] Supa, Michael, Cotzin, Milton, and Dallenbach, Karl M., FACIAL VISION: THE PERCEPTION OF OBSTACLES BY THE BLIND, American Journal of Psychology, Volume LVII, Number 2, April 1944.

According to Supa et al., by the late nineteenth century Dresslar (Reference 39) and Heller (Reference 40) had established that sound waves provided an adequate physical basis for facial vision, but there remained some uncertainty about the human receptor used to interpret the information in the sound waves. Heller (Reference 40), for example, apparently was not prepared to abandon the possibility of pressure sensitivity in the forehead as the means of transduction.

Without convenient electronic means for controlling the production of sound, it proved difficult to conduct convincing experiments to demonstrate that human audition was sufficiently sensitive to serve as a basis for facial vision. Thus, even though it was shown half a century later that hearing was a necessary and sufficient condition for facial vision, speculation on the topic grew even more intense in the early twentieth century.

Javal (Reference 41) coined the term "sixth sense", which he felt was related in some way to ether waves. A series of German experimenters concerned with this "X-sense" explored temperature and pressure sensitivity, while others (e.g., Villey, (Reference 42) reconfirmed that the ears suffice to

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[39] Dresslar, A. B., ON THE PRESSURE SENSE OF THE DRUM OF THE EAR AND FACIAL VISION, The American Journal of Psychology, Volume 5, 1893, pp. 344-350.

[40] Heller, T., STUDIEN ZUR BLINDEN, Psychologie, 113, 1904.

[41] Javal, Emile, THE SIXTH SENSE, in ON BECOMING BLIND, 152-169, 1905.

[42] Villey, Pierre, THE WORLD OF THE BLIND: A PSYCHOLOGICAL STUDY, in Ammons et al. (see Reference 48).

explain the ability of the blind to avoid obstacles. Despite other reconfirmations of the auditory basis of facial vision, bizarre speculation on the matter continued. Romains (Reference 43) contended that Ranvier corpuscles in the skin functioned as low resolution "ocelles" (little eyes) in the blind. Dolanski (Reference 44) postulated that contractions of small muscles in the skin provided a physiological basis for sensitivity to objects at a distance. Mouchet (Reference 45) granted a role for subliminal auditory stimuli, but not for normal auditory sensation.

With the 1944 publication of Supa et al., reasonable speculation came to an end. They demonstrated that "aural stimulation is both necessary and sufficient for the perception of obstacles..." and that the pressure theory (sensitivity of the face and other exposed skin areas) was "untenable". As is often the case, however, mysterious causes were preferred to mundane explanations, and a spate of empirical studies of facial vision continued for several years. Worchel and Dallenbach (Reference 46) reported on five experiments showing that deaf-blind persons did not possess any facial vision, and

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[43]Romains, J., EYELESS SIGHT, in Supa et al. (see Reference 38).

[44]Dolanski, V., DO THE BLIND SENSE OBSTACLES? AND THERE WAS LIGHT, Année Psychologie 1, 8-12, 1931.

[45]Mouchet, E., UN NUEVO CAPITAULA DE PSICOFISIOLOGIA; EL TACTO A DISTANCI O SENTIBO DE LES OBSTACLOS EN LOS CIEGOS, Annals of Institutional Psychophysiology, University of Buenos Aires, 2, 419-441, 1938.

[46]Worchel, Philip, and Dallenbach, K. M., FACIAL VISION: PERCEPTION OF OBSTACLES BY THE DEAF-BLIND, American Journal of Psychology 60, 502-553, 1947.

that "the cutaneous surfaces of the external ears (meatuses and tympanums) are not sufficient for perception of obstacles". Cotzin and Dallenbach (Reference 47) documented human sensitivity to pitch changes in echoes associated with Doppler shifts at frequencies on the order of 10 kHz. Ammons et al. (Reference 48) further explored the acoustic parameters used to test subjects temporarily deprived of sight and hearing.

It is now amply clear that people do not possess any "sixth sense", "X-sense", or nonauditory pressure sensitivity that can be used to detect the presence of objects at a distance. Nonetheless, the appeal of such notions is considerable; they have persisted for over two centuries of recorded speculation and during more than half a century of increasingly rigorous scientific investigation. For present purposes, nonauditory sensitivity to helicopters can be excluded from further consideration.

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[47] Cotzin, Milton, and Dallenbach, Karl M., FACIAL VISION: THE ROLE OF PITCH AND LOUDNESS IN THE PERCEPTION OF OBSTACLES BY THE BLIND, American Journal of Psychology, Volume LXIII, Number 4, October 1950.

[48] Ammons, Carol H., Worchel, Philip, and Dallenbach, Karl M., FACIAL VISION: THE PERCEPTION OF OBSTACLES OUT OF DOORS BY BLINDFOLDED AND BLINDFOLDED DEAFENED SUBJECTS, American Journal of Psychology, Volume LXVI, Number 4, October 1953.

EFFECTIVE MASKING BANDWIDTH STUDY

METHOD

Five male and five female audiometrically screened observers (of 22.9 years average age) were paid at the rate of $3.00 per hour to detect sinusoids of various frequencies presented in a continuous noise background. All testing was conducted under free field listening conditions in the presence of continuous masking noise.

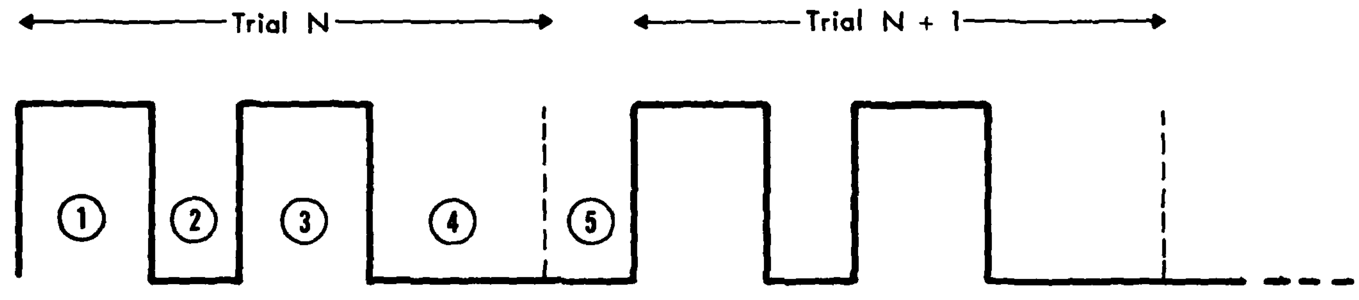
Observers detected sinusoids at 1000, 500, 250, 125, 63, and 40 Hz in a two-alternative forced choice task, in which they were instructed to press a switch corresponding to the time interval in which a signal was thought to occur (see Appendix A for instructions to testees). Preliminary training was accomplished at 1000 Hz to acquaint observers with trial procedures. Five hundred or more practice trials at various signal-to-noise ratios were administered until detection performance was judged to be sufficiently stable for data collection to start.

All testing at each frequency was completed before testing began at another frequency. The order of presentation of different frequencies was randomized over observers. All data at a given frequency were collected from each observer during the same day. An individual experimental session lasted about 2 hours, with frequent rest breaks between blocks of trials. Observers returned to the laboratory for several days to complete the schedule of data collection.

Detection performance at each frequency was assessed at several different signal-to-noise ratios. These ratios, generally about 1.5 dB apart, were selected on an individual basis for each observer to span the linear portion of the psychometric function (about 60 to 90 percent correct detection). In general, signal-to-noise levels decreased monotonically over successive blocks of trials, to avoid large changes in signal to noise ratios which can temporarily degrade detection performance. Determinations of detection performance at some signal to noise ratios were repeated as time permitted. This was done especially when an observer's alertness was in doubt, or if an anomaly of some sort was evident from psychometric functions plotted during data collection.

The time course of an individual trial is represented in Figure 4. The first observation interval, of 750 milliseconds duration, was separated from the second observation interval (of the same duration) by an interval of 500 milliseconds. The response and feedback interval, of 1000 milliseconds duration, immediately followed the second observation interval. If a response was made during this last interval, the response switch corresponding to the interval in which the signal actually occurred was lighted. An intertrial period of 500 milliseconds separated successive trials. Trials were administered in blocks of 100. Detection performance (percent correct) and the amount of the bonus (see Appendix A) paid were announced immediately after each block.

Each block of 100 trials was preceded by 10 practice trials. The signal level of the first of these practice trials was 5 dB higher than for the 100 trials during which detection performance was recorded. The signal level decreased 0.5 dB per



1. OBSERVATION INTERVAL 1 - 750 milliseconds
2. INTRATRIAL INTERVAL - 500 milliseconds
3. OBSERVATION INTERVAL 2 - 750 milliseconds
4. RESPONSE/FEEDBACK INTERVAL - 1000 milliseconds
5. INTERTRIAL INTERVAL - 500 milliseconds

Figure 4. Time Course of Two-Alternative Forced Choice Time Procedure.

practice trial until it reached the level at which it remained constant for the remainder of the block. The intent of providing 10 "practice" trials at the start of each block was to familiarize observers with the pace of data collection and to direct the observer's attention to the signal to be detected. These measures (the initially elevated signal-to-noise ratio at the start of each block, the descending staircase of levels, and practice trials in the amount of 10 percent of actual data collection) were taken to minimize observer variability in detection performance.

Data were collected in an anechoic chamber with a cutoff frequency of approximately 100 Hz. Care was taken to fix the observer's head position (by plumb bob) to minimize variability in absolute signal and noise levels associated with standing waves at lower frequencies. It should be noticed that the relative levels of signal and noise were unaffected by spatial variability in absolute level, since both signal and noise were produced by a single loudspeaker.

The absolute level of the Gaussian (white) masking noise was determined by four constraints. Most importantly, it could not be of such a level as to pose any significant risk of even temporary hearing impairment. Second, it could not be so subjectively annoying over its full bandwidth as to preclude completion of an extensive test program that required observers to return to the laboratory on separate days for testing at different frequencies. Third, the level had to be high enough that it would mask pure tones presented at least 10 dB above the human threshold of audibility. Fourth, the masking noise level had to exceed the ambient noise level in the anechoic chamber by at least 10 dB at all frequencies.

The net effect of these constraints was to require testing at four frequencies (1000, 500, 250, and 125 Hz) in a background noise environment with an upper band limit of 2 kHz and a spectrum level of 40 dB, and testing at three frequencies (125 Hz, 63 Hz, and 40 Hz) in a background noise environment with an upper band limit of 500 Hz and a spectrum level of 60 dB. The overall level of the background noise was less than 85 dB in the wideband condition, thus posing a negligible risk to hearing. The overall level of the noise was only a few dB higher in the narrowband condition than in the wideband condition, even though its spectrum level was 20 dB greater. The risk of hearing impairment from exposure to the higher spectrum level background noise in the narrowband condition was also negligible, both because its overall level was only about 87 dB, and because its highest frequency (500 Hz) is several octaves lower in frequency than noise that is thought to pose a significant hazard to hearing.

The mechanics of data collection were under computer control. Software prompted the experimenter to enter all information needed for acoustic calibration, identification of data, and selection of the signal-to-noise ratio at which testing was to commence. The software then administered practice trials, recorded data, and printed block statistics in real time. The software also recommended to the experimenter the signal-to-noise ratio for the next block of trials that would focus attention on the middle of the linear portion of the psychometric function. Figure 5 is a sample of the block statistics printed by the computer-based data collection system. Further detail of the equipment used to generate and measure acoustic signals may be found in Appendix B.

APPLIED TECHNOLOGY LABORATORY BANDWIDTH STUDY

TWO ALTERNATIVE FORCED CHOICE DETECTION TASK

BOLT BERANEK AND NEWMAN JOB NUMBER 08739

DATE: 11-13-78 SESSION #: 1 SUBJECT #: 3 EXPERIMENTER: SRT SIGNAL #: 250 BACKGROUND NOISE: WIDE 14:44:11

CURRENT BLOCK			SIGNALS		RESPONSES			---CUMULATIVE INFORMATION---	
TIME	% CORRECT	S/N (DB)	INTERVAL 1	INTERVAL 2	INTERVAL 1	INTERVAL 2	MEAN LATENCY	% MISSING DATA	RESPONSE BIAS
14:51:25	77.0	17.3	53	47	52	48	366 MSEC	0.0	101.9
14:58.16	67.0	14.3	53	47	50	50	266 MSEC	0.0	103.9
15:07:26	71.0	12.8	50	50	45	55	366 MSEC	0.0	106.1
15:16.27	70.0	11.3	49	51	53	47	367 MSEC	0.0	102.5
15:23:51	47.0	9.8	53	47	56	44	353 MSEC	0.0	100.7

Figure 5. Sample of Block Statistics Printed by Computer-Based Data Collection System for Bandwidth Study.

RESULTS

More than 55,000 trials were administered to the 10 observers in the various noise bandwidth and signal frequency conditions. Raw data (percent correct detections per block of 100 trials) for all observers are plotted in Figures 6 through 12 for each signal frequency.

Best fitting lines to these data were obtained for each observer and each frequency by calculating least-square regression solutions to points in the linear portions of the psychometric functions, from 60 to 90 percent correct detection. Points outside the 95 percent confidence interval at any level of performance were excluded from the regression equations. The confidence interval for each percentage correct detection was calculated from the binomial distribution as $\pm$ 1.96 $(pq/N)^{1/2}$, where N = 100, p = percent correct detection, and q = 1-p. The slopes and intercepts of these regression equations were then averaged over observers at each frequency, to yield the best fitting lines displayed in Figure 13.

These averaged regression equations were then used to predict three different levels of detection performance at each frequency. These data are plotted together in Figure 14. Differences in signal-to-noise ratio for comparable detection performance (in dB re signal-to-noise ratio needed at 1 kHz) may be found in Table 3. It is from these data that effective masking bandwidths were inferred by Fletcher's critical ratio method.

Estimated bandwidths are simply proportional to the change in signal-to-noise ratio needed to maintain constant detection performance at frequencies lower than 1 kHz, as seen in Table 3.

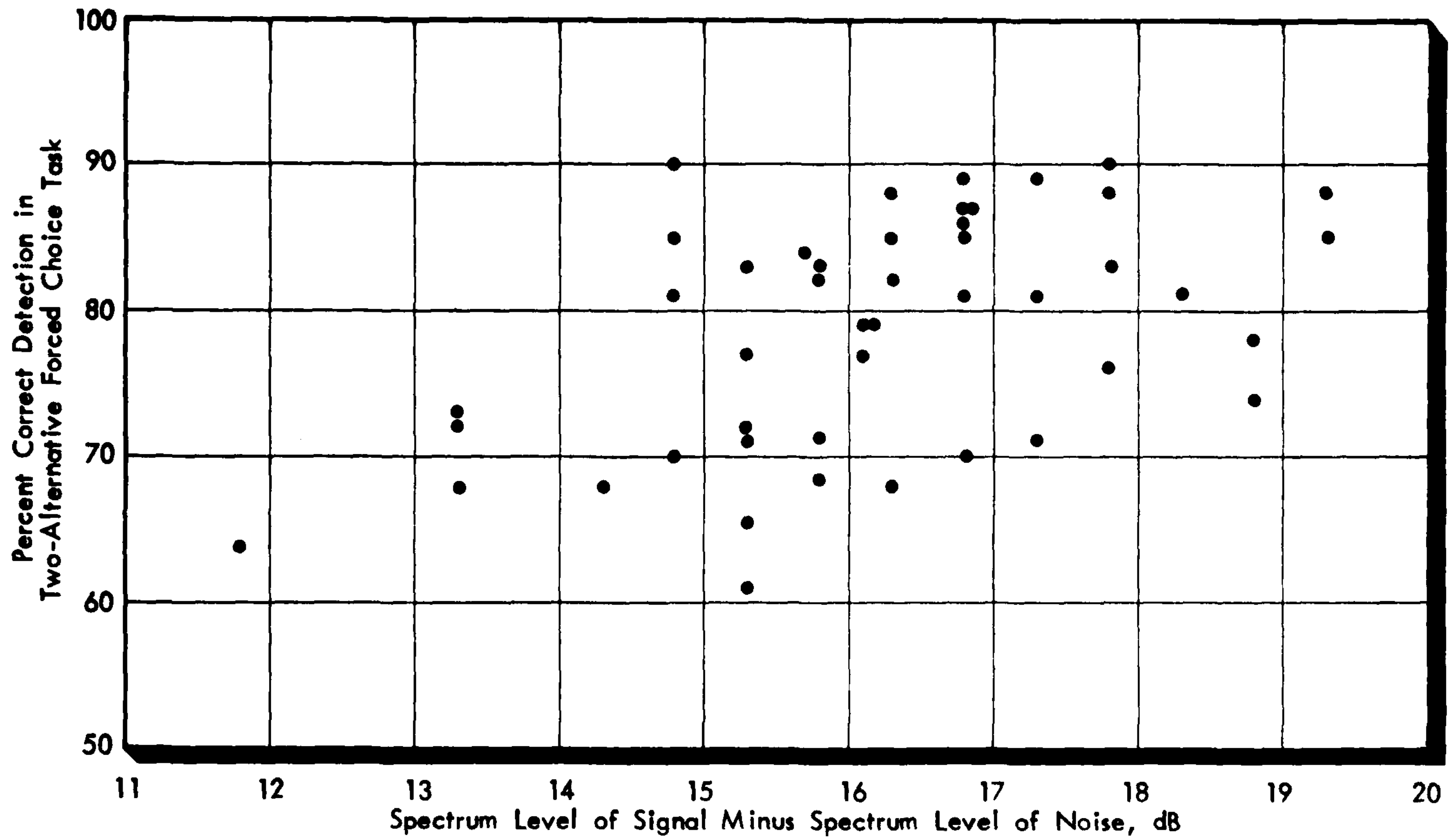


Figure 6. Detection Performance of All Observers at 1000 Hz.

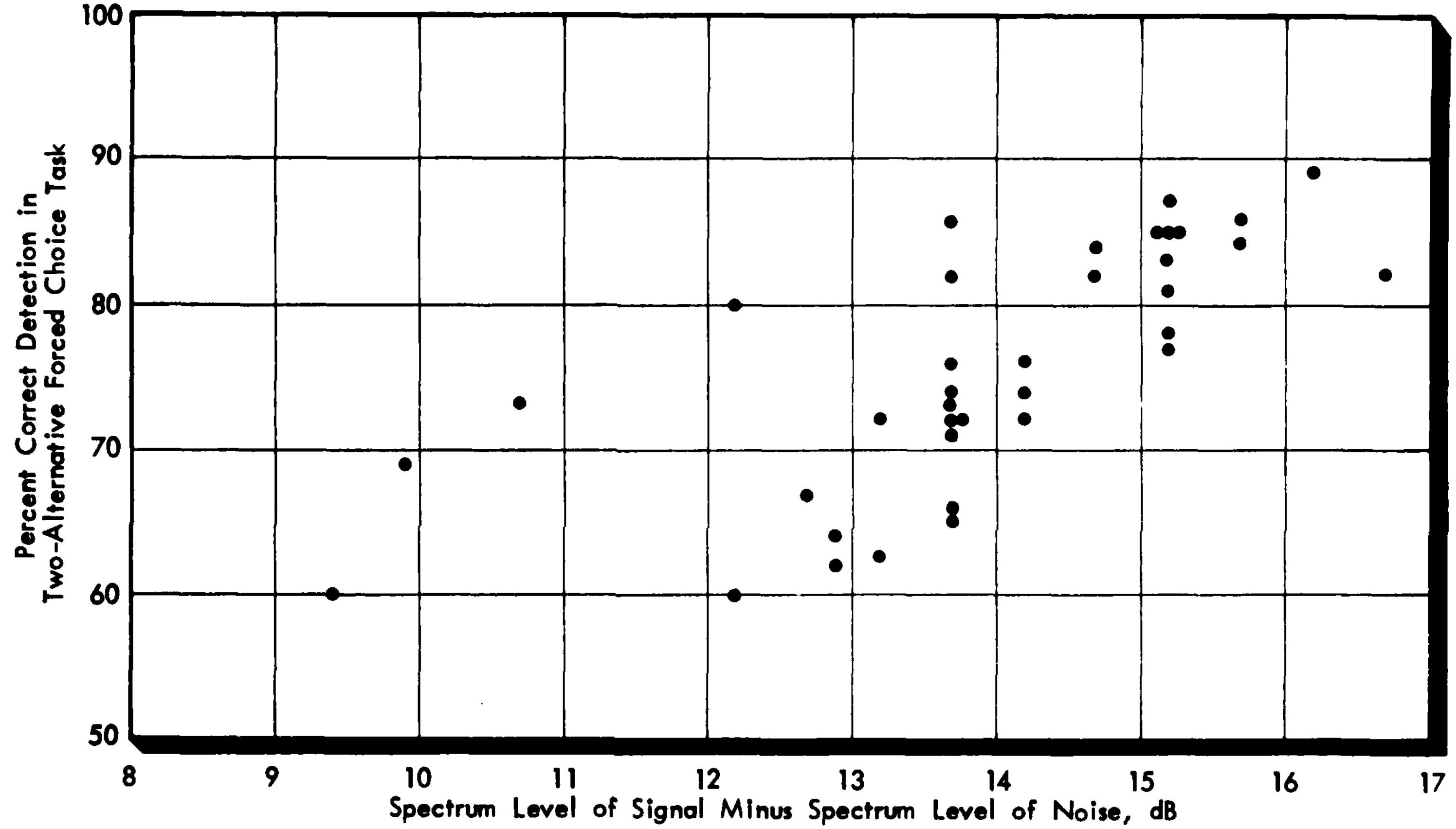


Figure 7. Detection Performance of All Observers at 500 Hz.

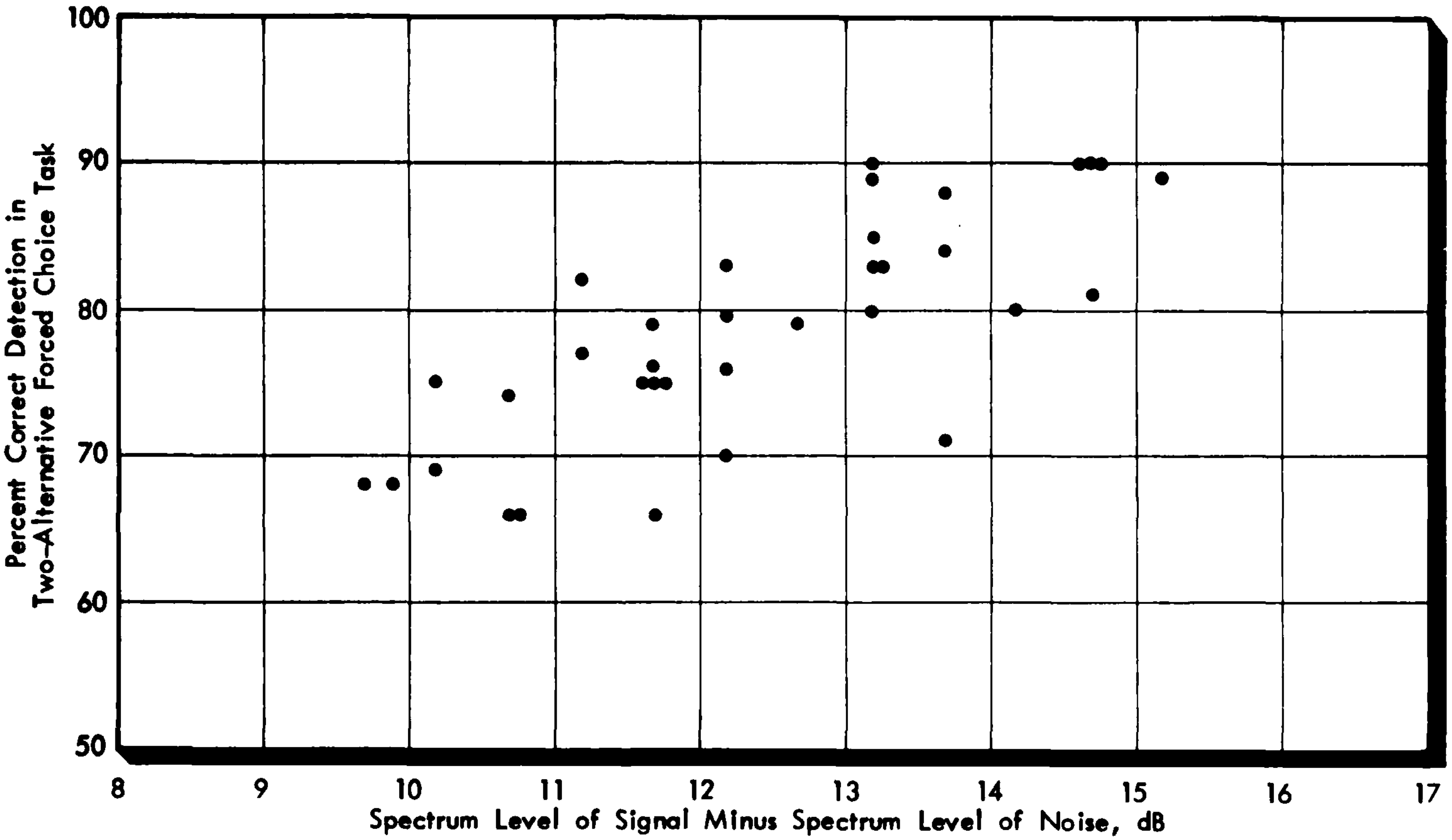


Figure 8. Detection Performance of All Observers at 250 Hz.

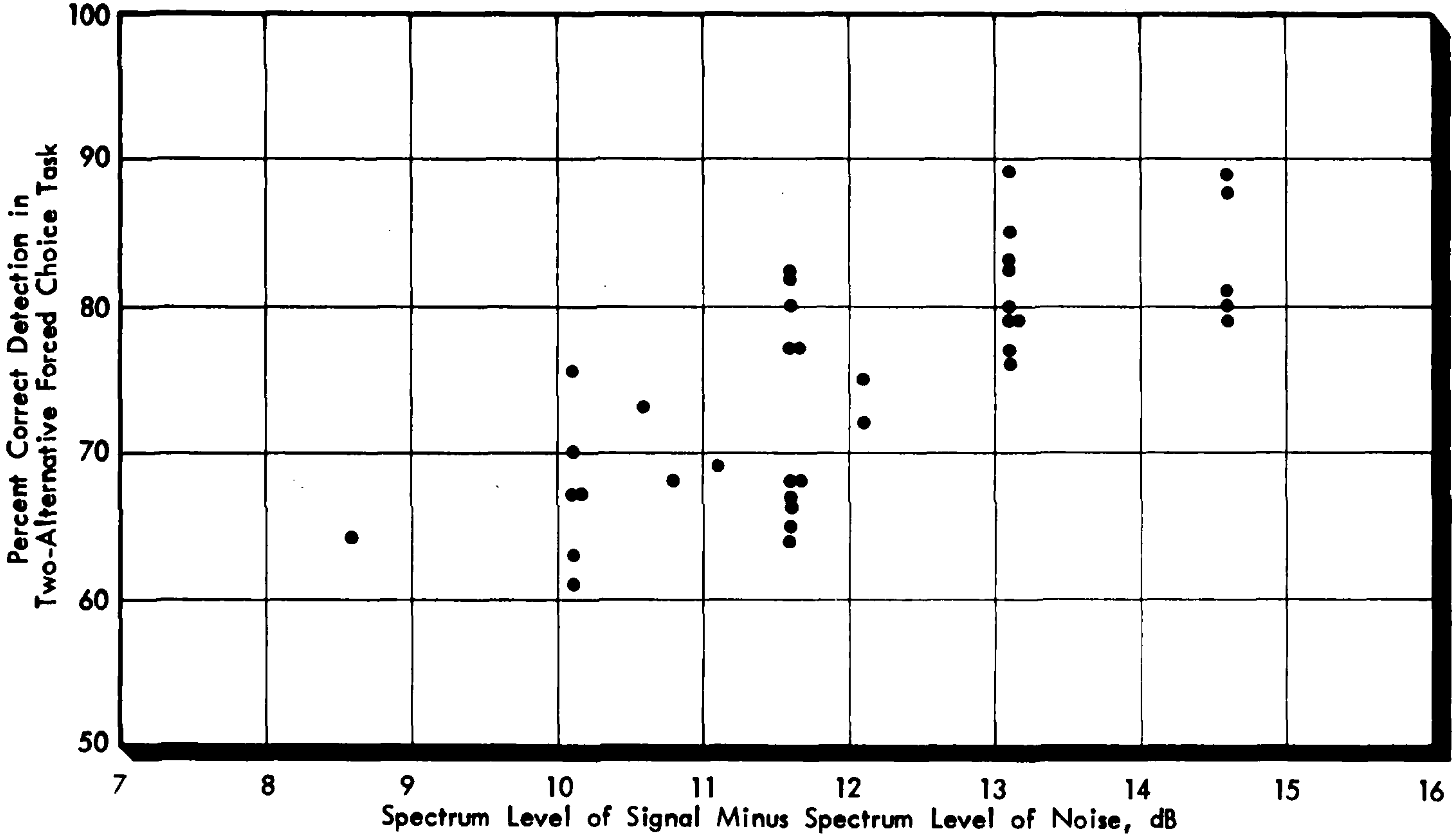


Figure 9. Detection Performance of All Observers at 125 Hz Wideband.

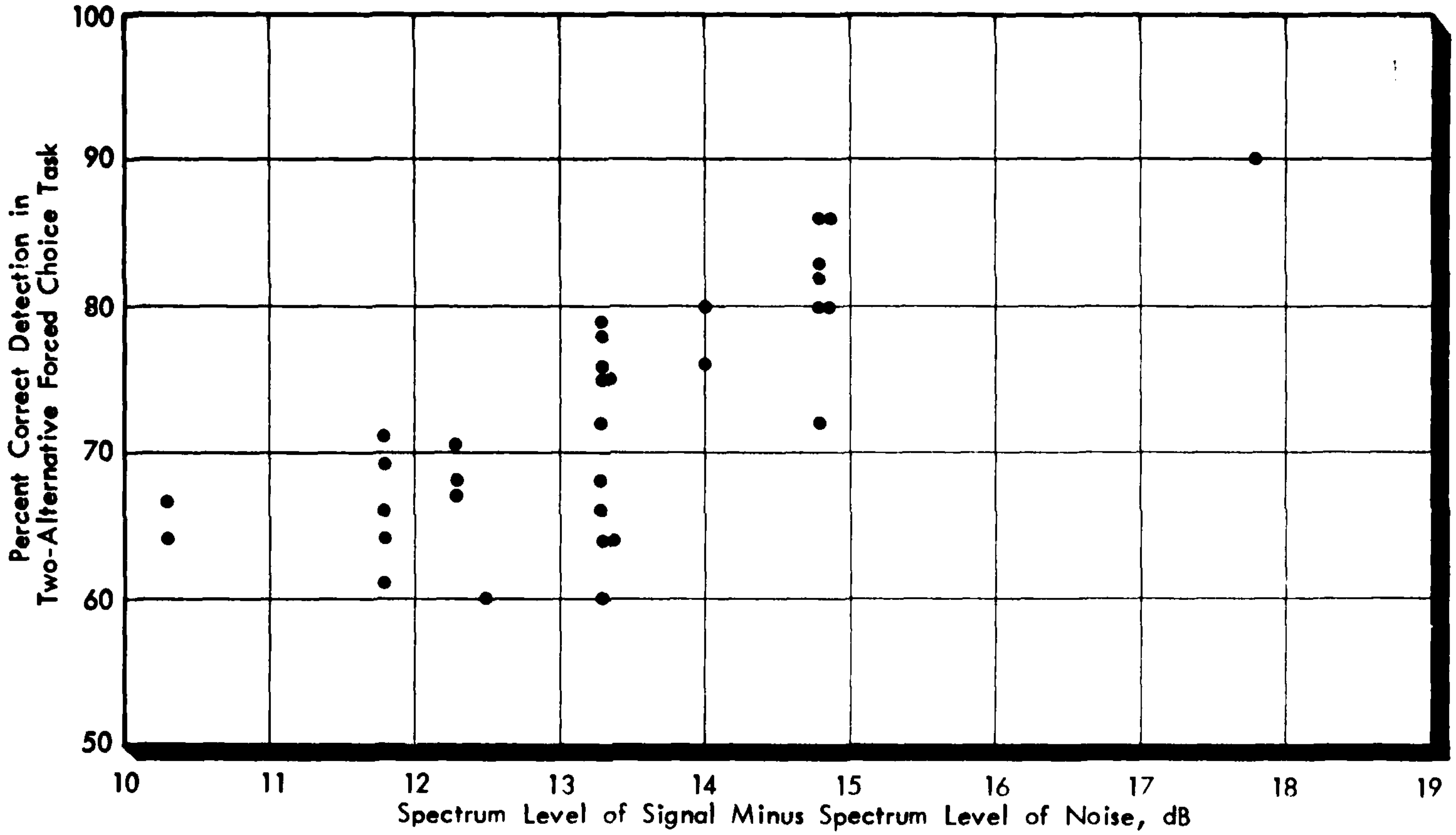


Figure 10. Detection Performance of All Observers at 125 Hz Narrowband.

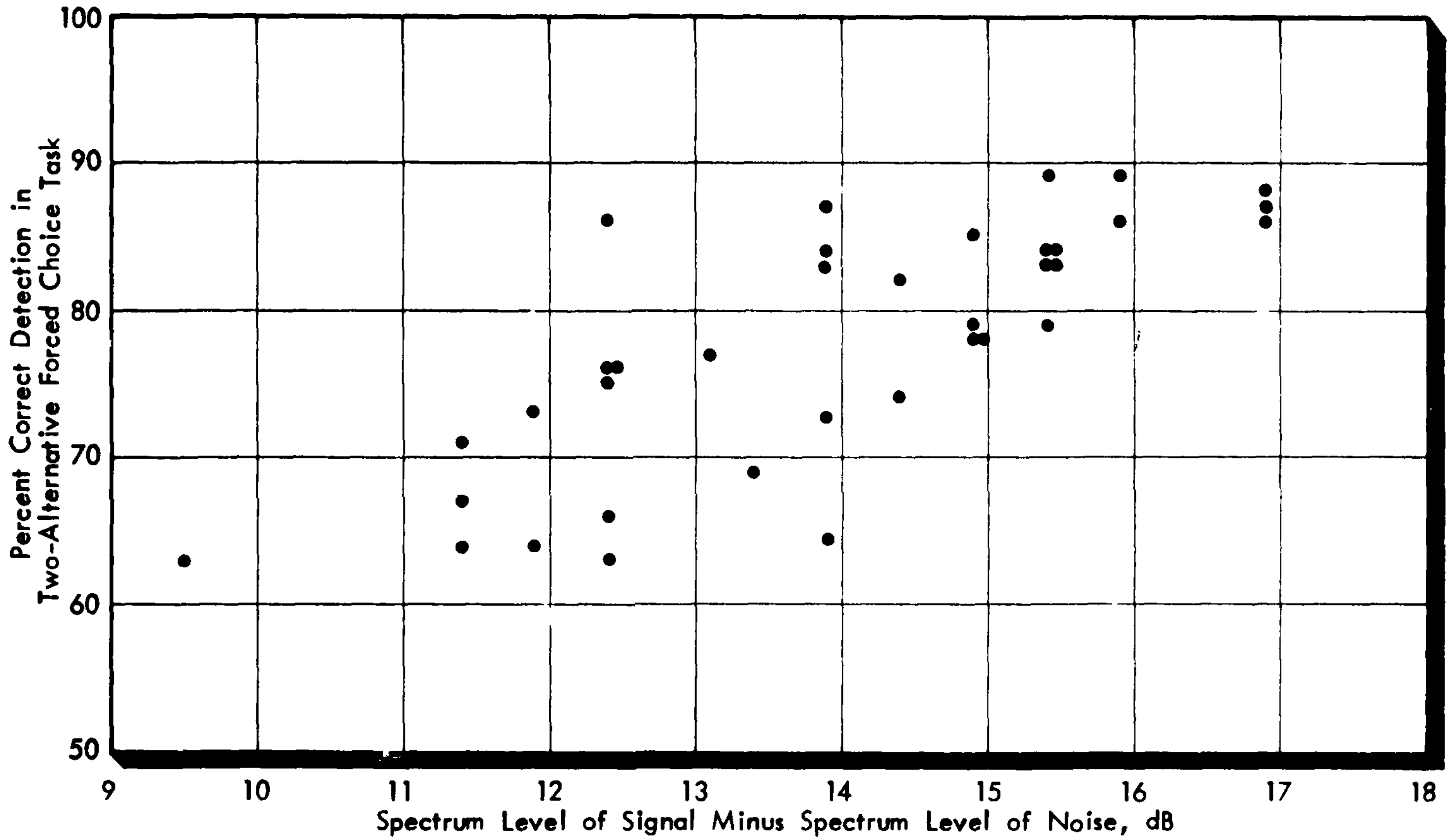


Figure 11. Detection Performance of All Observers at 63 Hz.

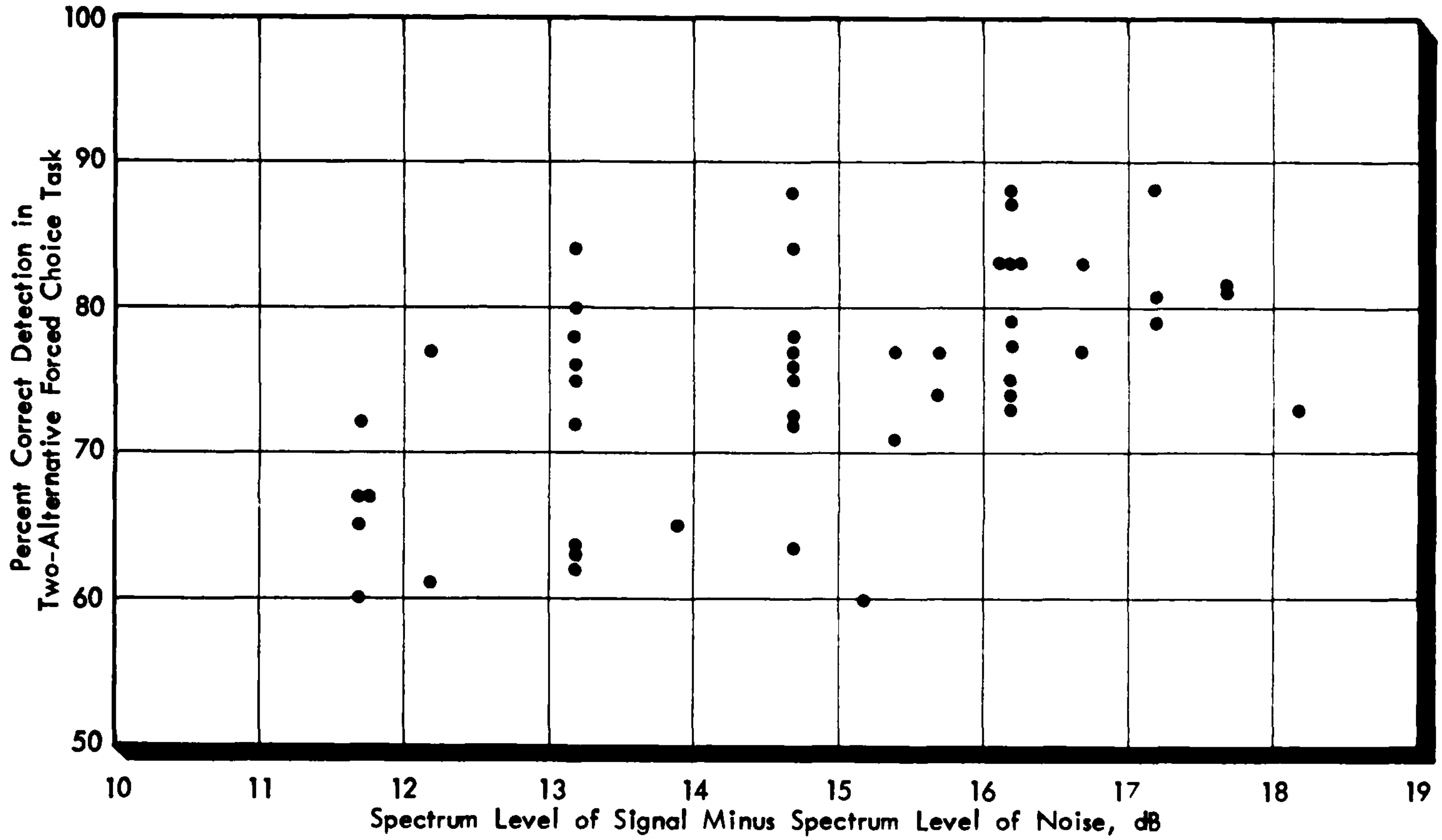


Figure 12. Detection Performance of All Observers at 40 Hz.

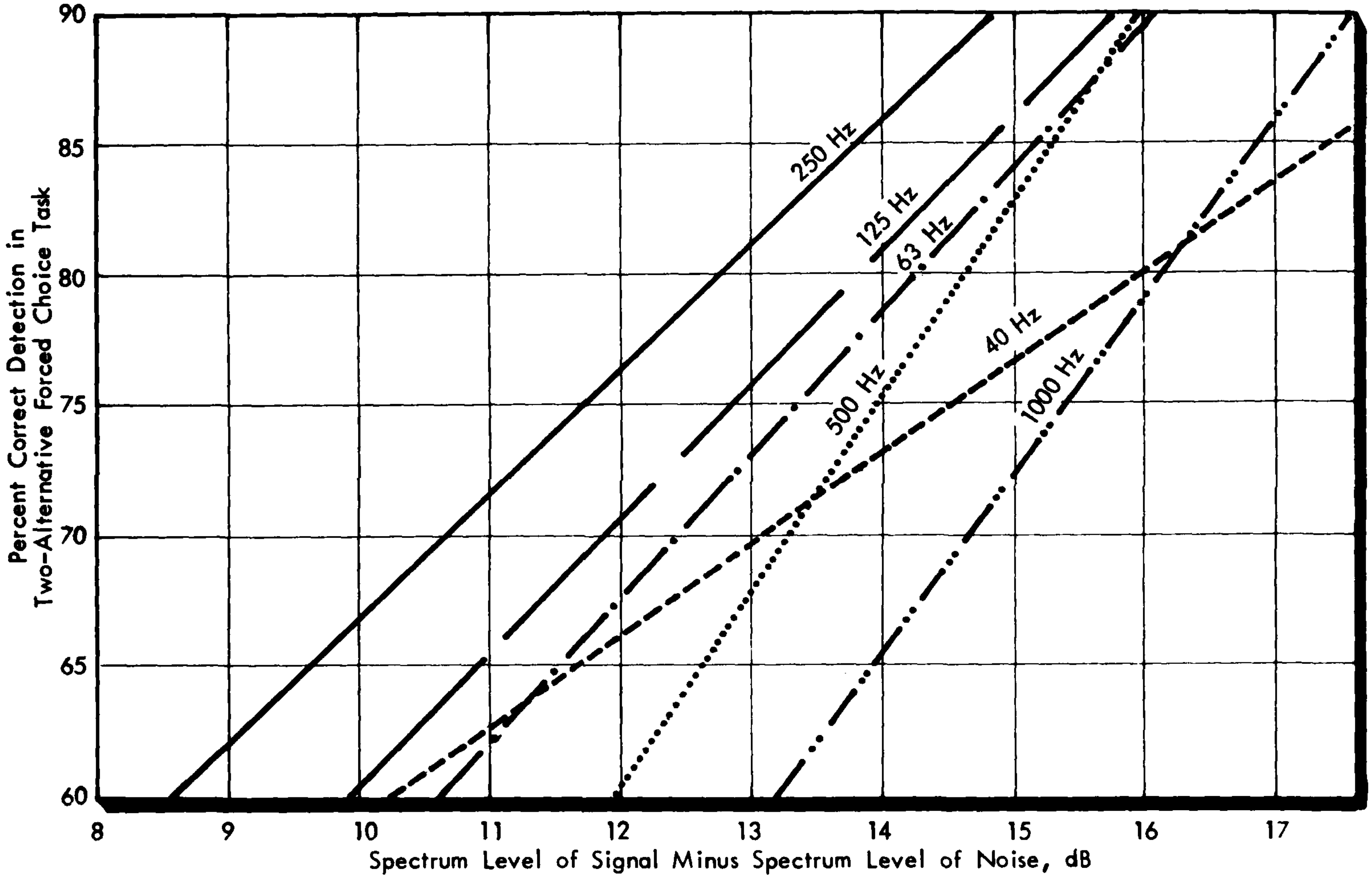


Figure 13. Slopes of Regression Lines For Linear Portions of Psychometric Functions at Six Frequencies.

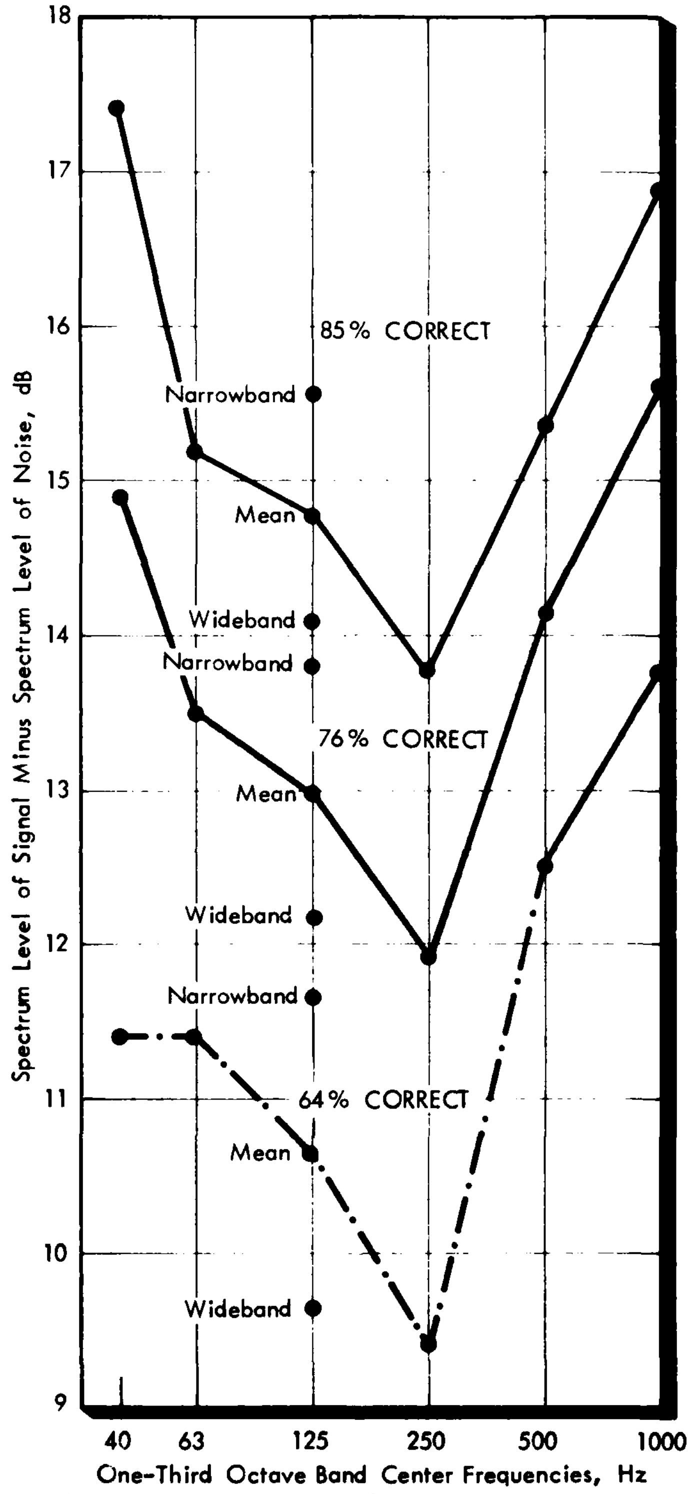


Figure 14. Average Signal-to-Noise Ratio For Constant Levels of Detection Performance Estimated From Individual Data at Six Frequencies.

TABLE 3.

ESTIMATED EFFECTIVE MASKING BANDWIDTHS AT SIX FREQUENCIES

FRE-QUENCY	S/N FOR 76% CORRECT IN BROADBAND NOISE (N_o = 40 dB)	S/N FOR 76% CORRECT IN NARROWBAND NOISE (N_o = 60 dB)	S/N FOR 76% CORRECT ADJUSTED TO N_o = 40 dB	ASSUMED BANDWIDTH
1000 Hz	15.6 dB	-- dB	15.6 dB	153.3 Hz*
500	14.1	--	14.1	109
250	11.9	--	11.9	66
125	12.2	13.8	12.2	70
63	--	13.5	11.9	66
40	--	14.9	13.3	90

*Forced to agree with Reference 1.

INFRASOUND STUDY

METHOD

Ten male and ten female audiometrically screened observers (of 21.5 years average age) were paid at the rate of $3.00 per hour to detect either or both of two signals in a two-alternative forced choice task in a continuous white noise background. The two signals were (1) a helicopter-like signal consisting of a repeated train of impulses and shaped noise, and (2) a pure tone at 15 Hz. The first signal was present in one of the two observation intervals of each trial. The probability of occurrence of the second signal was 0.5. On trials during which the second signal was presented, it occurred during the same observation interval as the first signal. Each block of 100 trials thus contained approximately 50 trials during which infrasound was present and approximately 50 trials during which infrasound was absent.

The observers' instructions (Appendix A) encouraged attention to the infrasonic signal by awarding a sizeable bonus for higher levels of detection performance on trials in which infrasound was present.

All testing was conducted in free field listening conditions under computer control. Each observer's participation in the experiment was completed during a single 2-hour session, in which approximately nine blocks of trials (containing about 450 trials with infrasound and 450 without infrasound) were administered. Testing was conducted at several different signal-to-noise ratios for each observer, to explore any

possible interaction between the efficacy of "infrasonic cueing" and the ease of the detection task.

All other conditions of data collection were similar to those of the effective masking bandwidth study. Figure 15 is a sample of the block statistics printed by the computer-based data collection system. Further detail of equipment used to generate signals and methods used to measure and calibrate acoustic quantities may be found in Appendix B.

RESULTS

Table 4 contains data averaged over all observers by signal-to-noise ratio. Column 1 contains data for trials with infrasonic cueing, while Column 2 contains data for trials without infrasonic cueing. A one-way analysis of variance conducted on these data revealed no significant differences in detection performance (F with 1 and 14 degrees of freedom was 4.6×10^{6}). The failure to observe any effect of infrasonic cueing was not an artifact of averaging over observers. This is apparent from the fact that not one of the 20 observers attained a higher level of detection performance in the presence of infrasound than in its absence.

Figure 16 displays the data of Table 4 as a scatter plot. In this presentation, the solid line with slope = 1 represents all those points at which detection occurred equally well with and without the presence of infrasound. Note that observed levels of detection performance lie very close to this line, and well within the 95 percent confidence interval formed from the variance of the binomial distribution.

APPLIED TECHNOLOGY LABORATORY INFRASOUND STUDY

TWO ALTERNATIVE FORCED CHOICE DETECTION TASK

BOLT BERANEK AND NEWMAN JOB NUMBER 08803

DATE: 12-19-78 SESSION #: 2 SUBJECT #: 5 EXPERIMENTER: SRT SIGNAL #: 1 BACKGROUND NOISE: WHITE 11:19:41

		-------WITH INFRASOUND------			------WITHOUT-------		SIGNALS	RESPONSES	-CUMULATIVE INFORMATION-		
TIME	S:N	TRIALS	RESPONSES	% CORRECT	RESPONSES	% CORRECT	INTERVAL 1	INTERVAL 1	LATENCY	% MISSING	RESPONSE BIAS
11:27 12	-1.0	54	54	70.3	46	71.7	42	49	369 MSEC	0.0	85.7
11 33.58	-2 0	54	54	59.2	46	71.7	48	71	374 MSEC	0.0	75.0

Figure 15. Sample of Block Statistics Printed by Computer-Based Collection System for Infrasound Study.

TABLE 4.

AVERAGE PERCENT CORRECT DETECTIONS IN A TWO-ALTERNATIVE FORCED CHOICE TASK IN THE PRESENCE AND ABSENCE OF INFRASOUND

S/N	With Infrasound	Without Infrasound
4.0 dB	95.0 %	94.7 %
3.0	92.9	90.3
2.0	86.8	86.8
1.0	81.0	82.2
0.0	79.7	78.0
-1.0	73.4	72.9
-2.0	63.2	66.2
-3.0	59.9	60.7

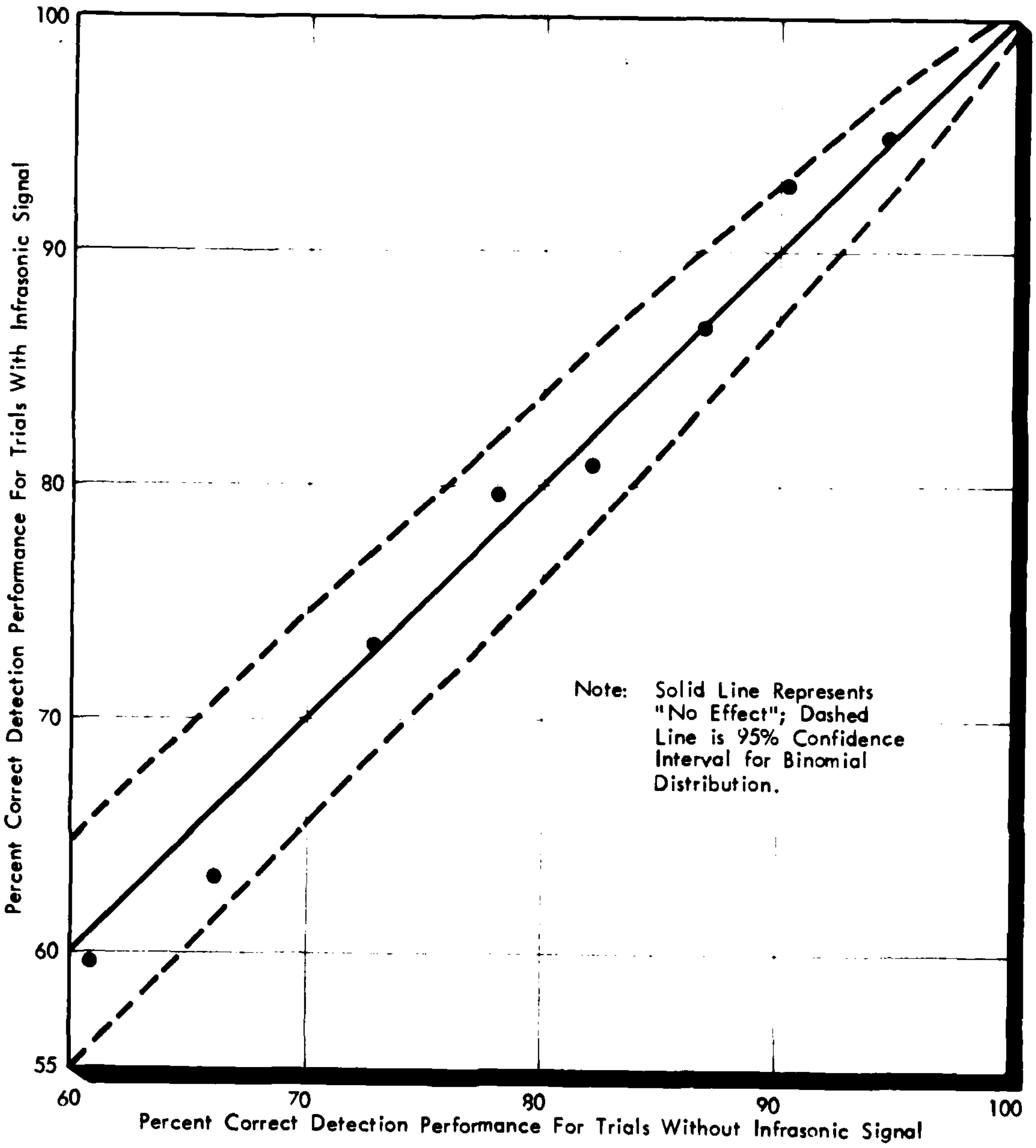


Figure 16. Relationship Between Detection Performance With and Without Infrasonic Cueing.

DISCUSSION

EFFECTIVE MASKING BANDWIDTH STUDY

The effective masking bandwidth estimates of Table 3 represent the most comprehensive estimates currently available in the low frequency region. As such, their relationship to prior data is of considerable interest.

One comparison that can be made between the present data and those of an earlier study is of the signal-to-noise ratio needed to just detect a sinusoid at 1 kHz. The current data are in excellent agreement with those of Hawkins and Stevens (Reference 20). Hawkins and Stevens, using a psychophysical method in which observers had essentially unlimited time to listen to the sinusoid and adjust its level, determined that a signal-to-noise ratio at 1 kHz (spectrum level of signal versus spectrum level of masking noise) of 18 dB was needed at the masked threshold. Although it is not clear what probability of detection corresponds to this point, it seems likely that it is a value in the region of 0.8 to 0.9, since it would have been difficult for their observers to adjust the level of a signal that they could detect with any lower probability. The equivalent value of signal-to-noise ratio in the current study (corresponding to 85 percent correct in a two-alternative forced choice task, or a d' value of 1.5) was 17 dB. This excellent agreement at 1 kHz establishes a certain face validity for the critical ratio extrapolations used to estimate lower frequency masking bandwidths.

A slight discrepancy between the psychometric functions obtained in the narrowband and wideband conditions at 125 Hz is also worthy of comment. It was observed that the regression lines describing detection performance at a level of 76 percent correct (d' = 1) differed by 1.6 dB between the two conditions, with the greater signal-to-noise ratio needed in the narrowband condition. This finding is counterintuitive if bandwidth alone is considered to be the source of the discrepancy, since reduced masking energy would be expected to permit lower signal-to-noise ratios for constant detection performance. It was also the case, however, that the absolute level of the masking noise in the narrowband condition was 20 dB higher than in the wideband condition.

The relationship between absolute level and masking bandwidth has been noted by several investigators (References 49, 50, and 51). For example, Reed and Bilger (Reference 50) observed a 1.5 dB increase (in a 20 dB range) in signal-to-noise ratio for constant detection performance, a figure in excellent agreement with the current finding. It was therefore concluded that the differences in signal-to-noise ratio for

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[49]Weber, Daniel L., GROWTH OF MASKING AND THE AUDITORY FILTER, Journal of the Acoustical Society of America, Volume 62, Number 2, August 1977.

[50]Reed, Charlotte M., and Bilger, Robert C., A COMPARATIVE STUDY OF S/N_0 AND E/N_0, Journal of the Acoustical Society of America 53,No. 4, 1973.

[51]Bourbon, Walter T., Evans, Thomas R., and Deatherage, Bruce H., EFFECTS OF INTENSITY ON "CRITICAL BANDS" FOR TONAL STIMULI AS DETERMINED BY BAND LIMITING, Journal of the Acoustical Society of America 43, No. 1, 1968.

constant performance in the 125 Hz narrowband and wideband detection tasks were not attributable to background noise bandwidth nor to imprecision of measurement, but rather were a function of absolute level.

INFRASOUND STUDY

The results of the infrasound study were not ambiguous, although negative. No change to existing software is needed to account for the demonstrated inability of human observers to use infrasonic energy to improve acoustic detection performance. This finding is also consistent with the literature discussed in the review of human sensitivity to infrasound.

MODIFICATION OF SOFTWARE

From the results of the masking experiment (with an assumed bandwidth of 153.3 Hz for a masking band centered at 1000 Hz) data points of bandwidth versus center frequency are shown in Figure 17. A fourth order polynomial, least-squares fit to these data, was developed in the form

$$\frac{1}{BW} = a_o + a_1 \cdot CF + a_2 \cdot CF^2 + a_3 \cdot CF^3 + a_4 \cdot CF^4 \qquad (3)$$

where BW = masking bandwidth in Hz

CF = masking band center frequency in Hz.

Coefficient values were as follows:

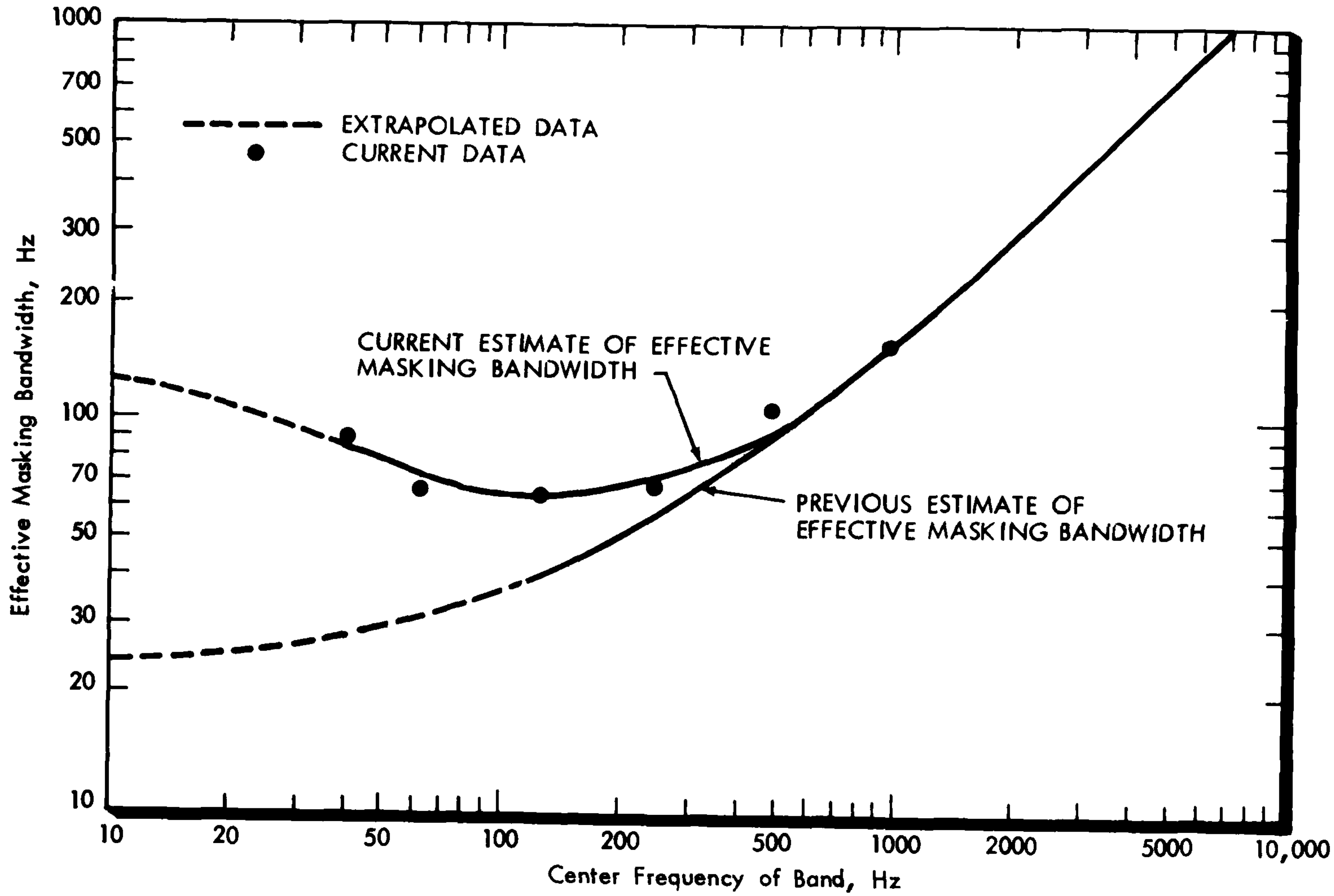


Figure 17. Current and Previous Estimates of Effective Masking Bandwidth.

$a_0 = 0.64842255 \cdot 10^{-2}$

$a_1 = 0.17178227 \cdot 10^{-3}$

$a_2 = 0.10411442 \cdot 10^{-5}$

$a_3 = 0.23652221 \cdot 10^{-8}$

$a_4 = 0.18670514 \cdot 10^{-11}$

The value 1/BW was chosen because it is the ratio of a 1 Hz wide band to that of a critical band, both centered at CF. Viewed another way, it is the fractional amount of a critical bandwidth represented by a 1 Hz change in absolute frequency, the rate of change in relative frequency with center frequency, or Δ RF/Δ CF. Thus, if this expression is integrated with respect to the center frequency, CF, a direct expression for relative frequency, RF, in Barks is obtained as

$$RF = K + a_o \cdot CF + \frac{a_1}{2} \cdot CF^2 + \frac{a_2}{3} \cdot CF^3 + \frac{a_3}{4} \cdot CF^4 + \frac{a_4}{5} \cdot CF^5 \qquad (4)$$

and:

$K = 3.774663085$

$a_o = 0.64842255 \cdot 10^{-2}$

$\frac{a_1}{2} = 0.85891135 \cdot 10^{-4}$

$\frac{a_2}{3} = -0.34704807 \cdot 10^{-6}$

$\frac{a_3}{4} = 0.59130553 \cdot 10^{-9}$

$\frac{a_4}{5} = -0.37341028 \cdot 10^{-12}$

where K is the constant of integration, chosen such that the numerical values of the above expression and that computed by the original computer program are equal at 500 Hz (see Figure 18).

Using such an approach, only a minor change to the computer program was required. This change involved substituting the above 6 constants for those on cards 553 and 554 in subroutine FUNKY.

VERIFICATION OF SOFTWARE CHANGES

Checkout of the modified detection software was accomplished by comparing the output of the original with the modified program for several combinations of signal and ambient noise conditions. Since the modifications affected only signal-to-noise ratio calculations, checkout concentrated on manipulations of sound pressure levels. A simple set of other physical parameters (such as air temperature, humidity, and ground cover) was used for all test conditions.

The first test case was detection of a white noise signal (equal energy per unit bandwidth) in the presence of a white noise ambient. A second test case was detection of a helicopter-like signal in the presence of three different ambient noise spectra. All tests were made with sound level information in a one-third octave band format.

White Noise Test Case

The intent of the white noise test case was to demonstrate that the original and modified programs generate identical results given signal and ambient noises of nearly

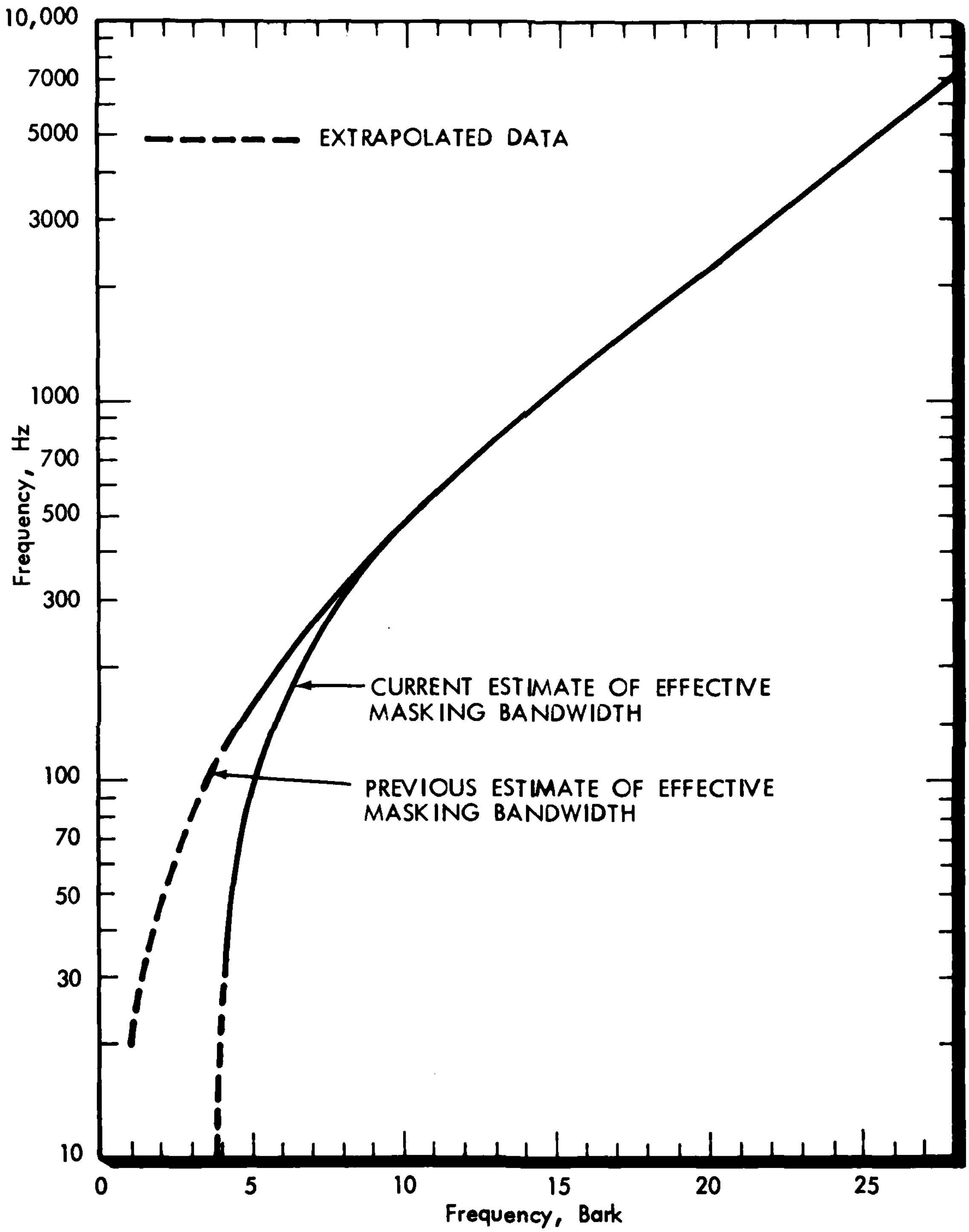


Figure 18. Current and Previous Estimates of Relationship Between Hertz and Bark.

identical spectral shape (air absorption effects will make the "signal" spectrum somewhat off-white when long propagation distances are involved). Because the signal-to-noise ratio calculated by the program at a specific masking band center frequency is invariant with bandwidth (since a change in bandwidth adds or subtracts equal proportions of energy to both the signal and the noise) the ratio between the two quantities remains unchanged for the case of white noise.

Two white noise tests were performed, one at very high sound levels (substantially above the threshold of hearing, even at low frequencies), and one at moderate levels. Both tests employed white signal and background noise spectra covering a frequency range of 11 Hz to 11,000 Hz. In both cases the background noise was set 30 dB lower than the signal at a distance of 1000 feet and an altitude of 200 feet. The high and low level tests used signal spectrum levels of 165.4 and 65.4 dB, respectively. Environmental parameters were set at 60° F, 9.3 g/m^3 absolute humidity, smooth surface and no wind. Masking bands were computed at 189 spectral points with 15 Hz resolution.

Comparison of the program output confirmed that the original and modified programs produced identical results for both the high and low level test cases.

Helicopter Spectrum and Quasi-Realistic Background Noise Test Case

The purpose of this case was to verify the effects of the software modification on a typical set of helicopter and background noise conditions. The spectral content of both the helicopter and the three ambient conditions is shown in

Figure 19. The reference distance and speed for the helicopter noise levels, as well as the atmospheric conditions, were those of the white noise test case. Masking bands were computed at 282 spectral points with 2 Hz resolution to adequately depict the low frequencies.

The results from both the original and the modified programs are shown in Figure 20. The figure contains three panels of the program's frequency versus distance printing format, one for each of three different ambient spectra acting as maskers for a common helicopter. The shaded bars show the difference in computed detection range between the original and the modified software for two levels of detectability.

A number of observations may be made about Figure 20. The first observation is that, as expected, the two programs produce identical results for frequencies of 500 Hz and greater (recall that program modifications affected only the spectral region <u>below</u> 500 Hz).

The second observation is that at lower frequencies the modified software generates greater detection ranges (with a few minor exceptions) than the original. This outcome is a function of the relative spectral shape of the helicopter and ambient sounds. The modified program can only generate greater detection ranges when the calculated signal-to-noise ratio at a given distance is numerically larger than in the original program. Since the only software change has been the widening of masking bands, a larger signal-to-noise ratio occurs only if the widened bands have admitted a greater proportion of helicopter noise than ambient noise. This happens when the spectral slope (rate of change of level with frequency) of

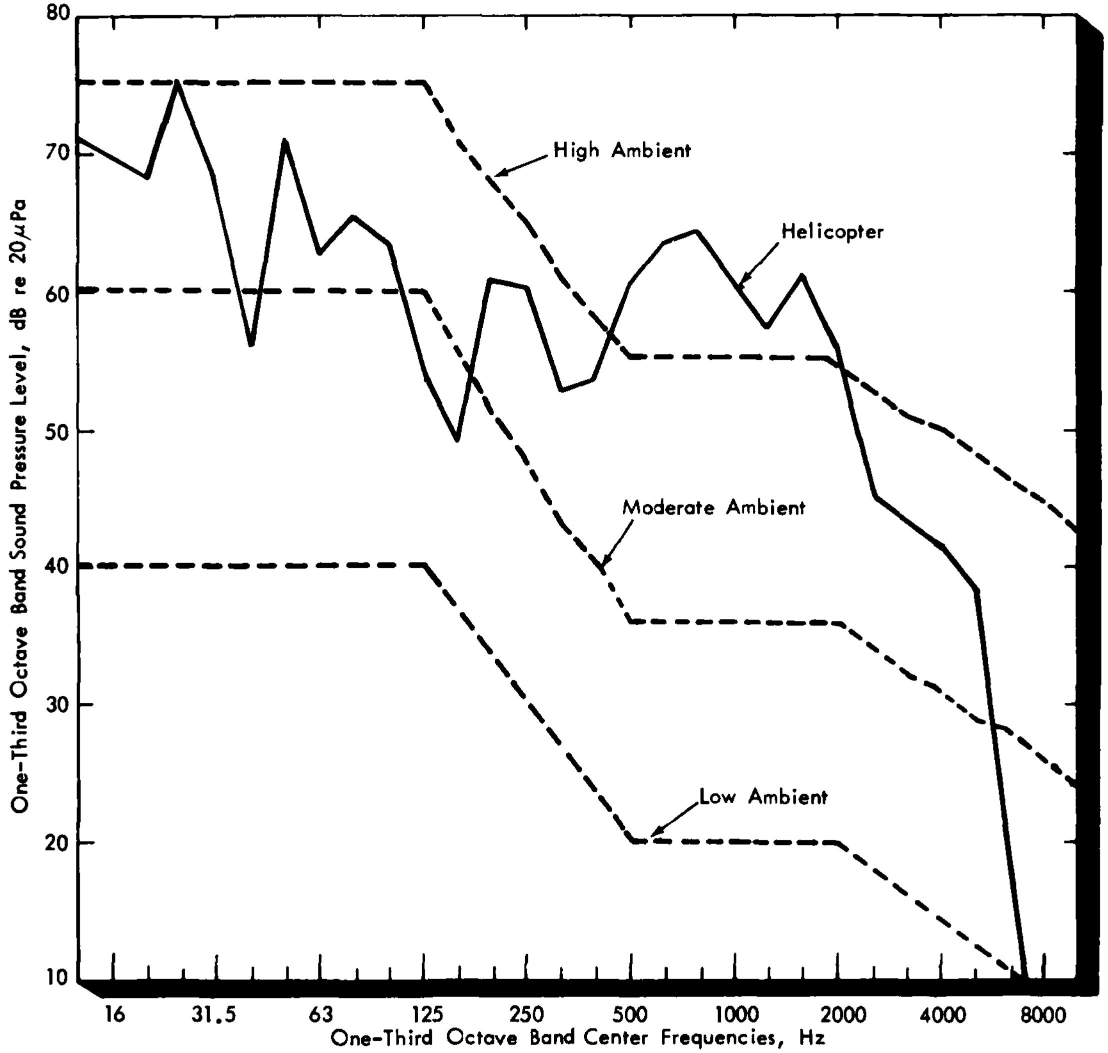
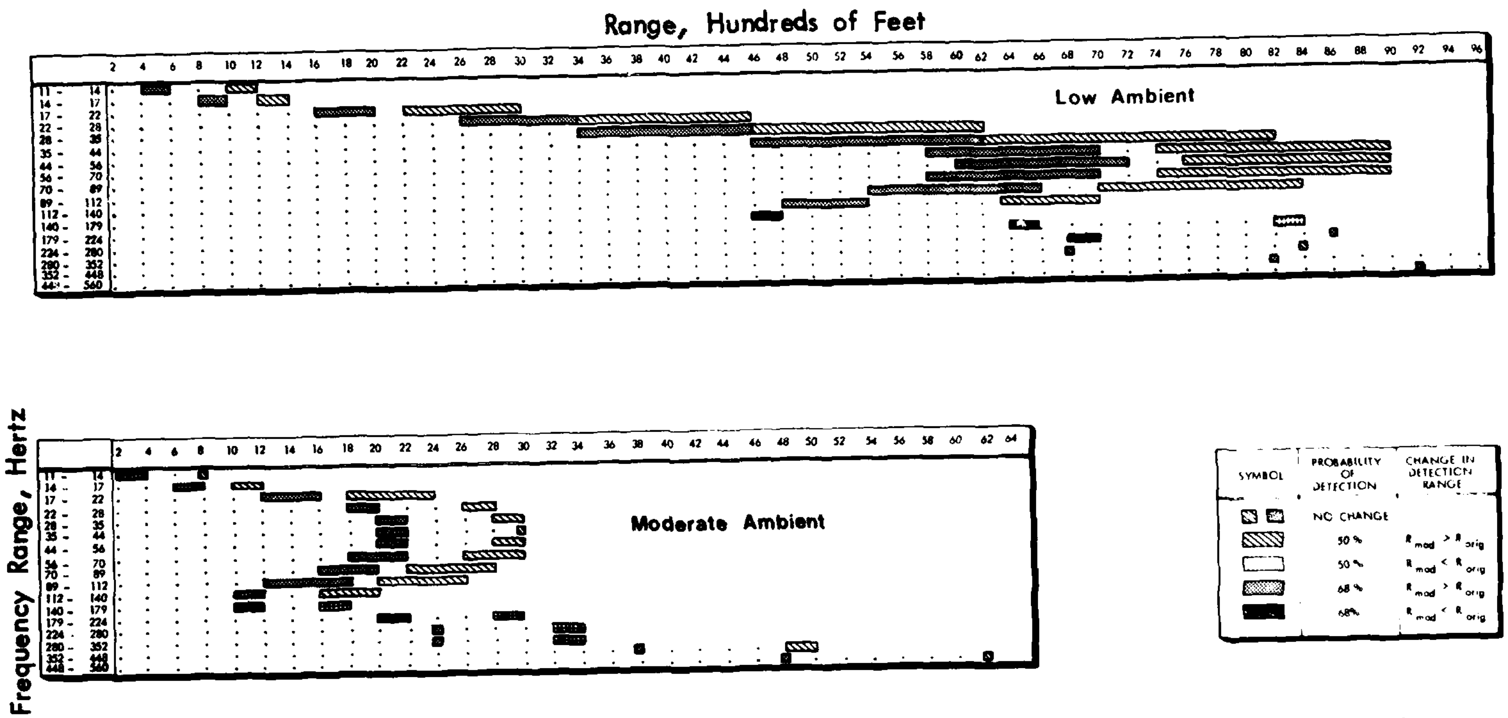
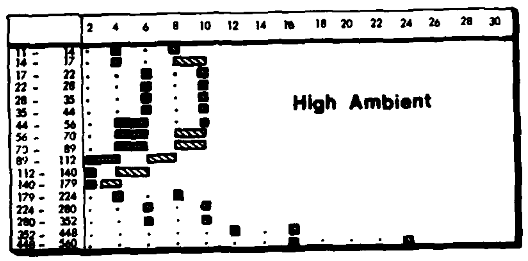


Figure 19. Helicopter and Ambient Spectra For Test Case.





Note: See Figure 19 for Helicopter and Ambient Spectra.

Figure 20. Example of Change in Predicted Detection Ranges Between Modified and Original Programs for Three Ambient Conditions.

the helicopter exceeds that of the ambient at the particular frequency of interest. Examination of the spectral shapes of the helicopter and ambient (Figure 19) confirm that this is indeed the case, especially in the range of 12 to 125 Hz, where the slope of the ambient is minimal. If the spectra of the ambient and helicopter were interchanged, the outcome would be reversed; that is, the original program would calculate greater detection ranges than the modified one.

In summary, the modifications produced results consistent with expectations. As a general rule, one may expect that below 500 Hz the modified software will produce greater detection ranges than the original program, when the spectral slope of the helicopter is greater than that of the ambient. When the slope of the ambient is greater than that of the helicopter, just the opposite effect will occur.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. The current study provided strong evidence that effective masking bandwidths (frequency regions within which noise interferes with the audibility of signals) at low frequencies are a non-monotonic function of frequency. Effective masking bandwidths decrease with frequency only to about 250 Hz, after which they again increase. The effective masking bandwidth at 40 Hz is nearly as great as at 500 Hz.

2. Modifications made to existing ATL software in accordance with this finding will in general produce greater detection range estimates than hitherto when the slope of a helicopter spectrum below 500 Hz exceeds that of the background noise environment in the same spectral region.

3. It was also demonstrated that infrasonic energy plays no significant role in acoustic detection of helicopters by unaided human observers.

RECOMMENDATIONS

1. A major remaining area of uncertainty about the ability of human observers to detect acoustic signals at low frequencies concerns the effects of signal duration. The relatively long signal durations at the present investigation (750 milliseconds) permitted exposure to only 30 full cycles of a 40 Hz tone, but 750 cycles of a 1 kHz tone. Changes in signal-to-noise ratio required to maintain constant detection performance at different frequencies were attributed in

the present study to changes in effective masking bandwidth. Such changes might arguably be ascribed to concomitant changes in effective signal duration. Recommend an empirical study be conducted, designed to separate temporal from frequency domain effects at low frequencies in order to help reduce this uncertainty. Such a study could provide further insight into the degree to which the observer's integration time affects detection performance at low frequencies.

2. Recommend a research program be initiated concerning the effects of the impulsiveness of helicopter noise signatures and temporal modulation on detectability. This would also be of value in refining the existing model.

3. Recommend a carefully designed field testing of portions of the acoustic detection model, to provide information useful for adjusting parameters of the model to observed levels of human performance.

4. Recommend further modification of ATL software to permit consideration of other propagation effects and other circumstances of human signal detection that are known to affect detection range predictions.

APPENDIX A
INSTRUCTIONS FOR BANDWIDTH STUDY

Your job in this experiment is to listen for one particular sound that the experimenter will play for you. This sound will always occur in either the first or the second of two brief listening periods. These pairs of listening periods (called trials) will be repeated many times, but your job will always be the same: to push button 1 or button 2 to tell us in which of the listening periods you think the sound you are listening for occurs. A special bonus payment (explained later) in addition to your hourly pay will be paid for the right answers.

The only way to correctly choose the listening period in which the sound occurred on a given trial is to listen carefully for the sound. It is equally likely on a given trial that the sound you are listening for will be in the first or second listening period. However, there will be absolutely no way to predict before a trial starts which of the two periods will contain the sound. Thus, if you guess at random you will be right only half of the time (and will earn no bonus).

The sound you are listening for will not always be easy to hear, because it will be heard in the presence of noise. In fact, on many trials you will have a hard time deciding whether the sound you are listening for is in the first or second listening period. Even when you are completely uncertain, however, it is to your advantage to guess, and we encourage you to do so. In order to be eligible for the bonus payment,

you must at least guess on each trial. Thus, there is no penalty for a wrong answer, but only a reward for a right answer.

The computer that is running this experiment will indicate when the two listening periods occur on each trial by lighting up your response buttons. You will know when a trial starts because the computer will light up button 1 to tell you that the first listening period has begun. At the end of the first listening period the light in button 1 will go out, and after a brief pause, the light in button 2 will come on to tell you that a second listening period has begun. YOU HAVE ONE SECOND after the light in button 2 goes out to decide which button to push. You must decide during this one-second time limit, because the next trial will start regardless of whether you have made up your mind.

The computer will keep track of your right and wrong answers and will tell you whether you were right or wrong immediately after you make your decision. If you do respond during the one second between trials, the computer will light up the button corresponding to the listening period that actually <u>did</u> contain the sound you were listening for in the previous trial.

The whole trial lasts only a few seconds, so you will need to practice for a while to get used to the pace of the experiment. Trials will be grouped together in "blocks" of 100, with a short break between blocks. Every few blocks you can rest in the coffee room for a few minutes. The experimenter will be able to see and hear you at all times while you are in this room.

INSTRUCTIONS FOR INFRASOUND STUDY

Your job in this experiment is to decide on each trial which of two observation intervals (marked "1" and "2" on your response switches) contains either of two sounds, which you will hear shortly. One of the sounds that you will be listening for is a repeated tap-tap-tap, while the other is a very low-pitched tone.

The tapping sound will always be present in one or the other of the two observation intervals at random. The low-pitched tone will be presented on only half of all trials at random. If the low-pitched tone is presented, however, it will occur in the same interval as the tapping sound. You should always listen for the low-pitched tone as well as the tapping sound, since the presence of the low-pitched tone may help you decide which observation interval contained the tapping sound.

To encourage you to remain alert, we will pay you two types of bonuses for each block of trials. One bonus will be paid simply on the basis of your total percent correct decisions per block. We will pay you one cent for every percent correct in excess of 65 percent correct. Thus, if your score is 85 percent correct for a block of trials, you will earn a 20-cent bonus for that block.

Additionally, your score will be figured separately for trials in which the two sounds occur together and trials in which only the tapping sound is presented. A second bonus will be paid if your score for trials in which both sounds are presented is higher than your score for trials in which

only the tapping sound is heard. This bonus will be paid at the rate of two cents for each percent correct by which your score for the trials with two sounds exceeds your score for the trial with only the tapping sound. Thus, if your percent correct for the trials with the tapping sound alone is 85 percent, and your score for the trials with both sounds is 95 percent correct, the second bonus will amount to another 20 cents.

The trial procedure will be explained to you before the first block of practice trials. If you have any questions, please ask the experimenter before or after a block of trials, since interruptions in the course of a block of trials will almost certainly result in a lower score. The experimenter can hear you at all times, and also see you on a television monitor, so if you must pause in the middle of a block of trials, simply tell the experimenter. Be careful not to change the seat position when sitting down or standing up, since it has been carefully arranged and must remain the same for all blocks of trials and all test subjects.

APPENDIX B
ACOUSTIC MEASUREMENTS

Acoustic calibration was accomplished in two independent sets of measurements: one using a Spectral Dynamics Corporation SD-360 digital signal processor, and another using a Hewlett-Packard Model 8054A real time audio spectrum analyzer in conjunction with a laboratory computer. The transducer used for both systems was a Bruel & Kjaer (B & K) Model 4131 1-inch condenser microphone with a General Radio Model 1560-P42 microphone preamplifier. The microphone was located at the seated test subjects' nominal head position (45 inches above the floor) in the anechoic chamber. Outside the chamber, the microphone preamplifier output was connected to a B & K Model 2203 precision sound level meter. The output of this sound level meter was (1) recorded on magnetic tape and (2) connected directly to the digital signal processor.

The digital signal processor is capable of dividing a specified frequency range into 1024 constant bandwidth components using fast Fourier transform techniques. Figures B-1 through B-3 were generated by this instrument. Figure B-1 displays the spectrum level of the two background noise environments employed in this experiment. The ordinate is the spectrum level (i.e., dB per 1 Hz bandwidth) and the abscissa is the frequency in Hz. Note that the broadband background contains energy from about 11 Hz to 2000 Hz, whereas the narrowband background contains energy from about 11 Hz up to only 400 Hz. Note also that other than a 20 dB difference in spectrum level, the frequency content of the two backgrounds is identical below 400 Hz.

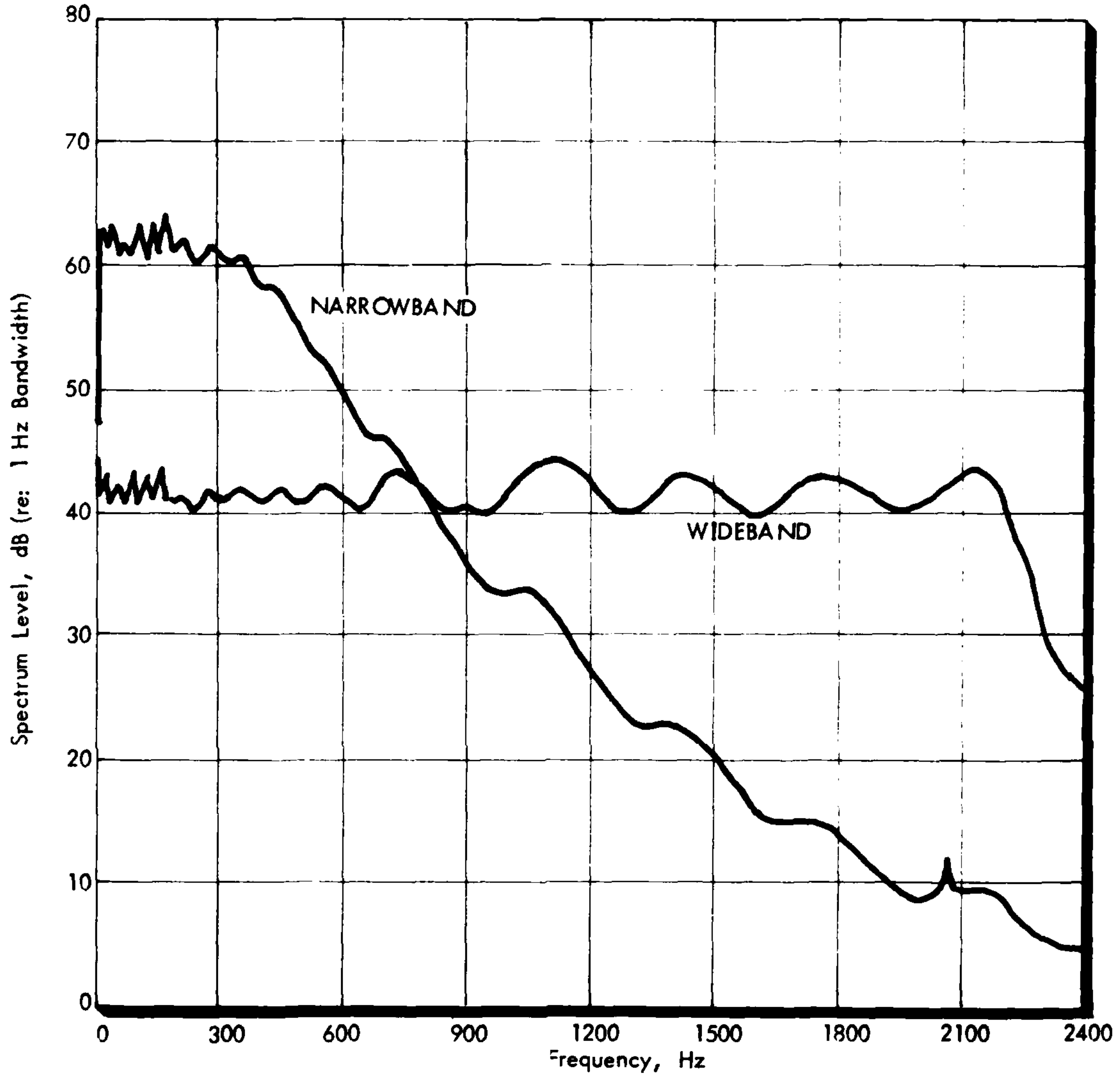


Figure B-1. Spectrum Level of Masking Background Noise Environments.

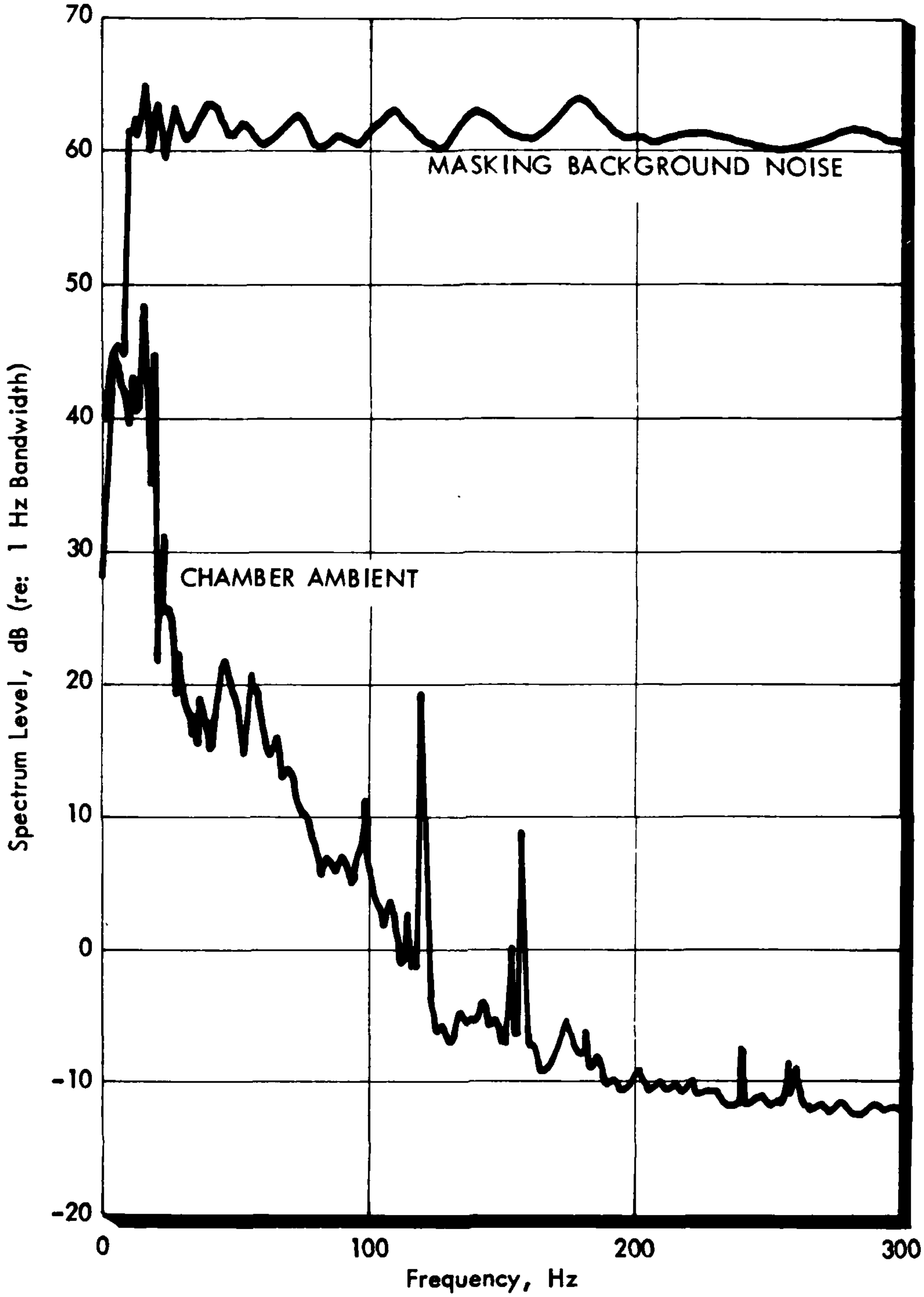


Figure B-2. Spectrum Level of Narrowband Masking Noise and Anechoic Chamber Ambient.

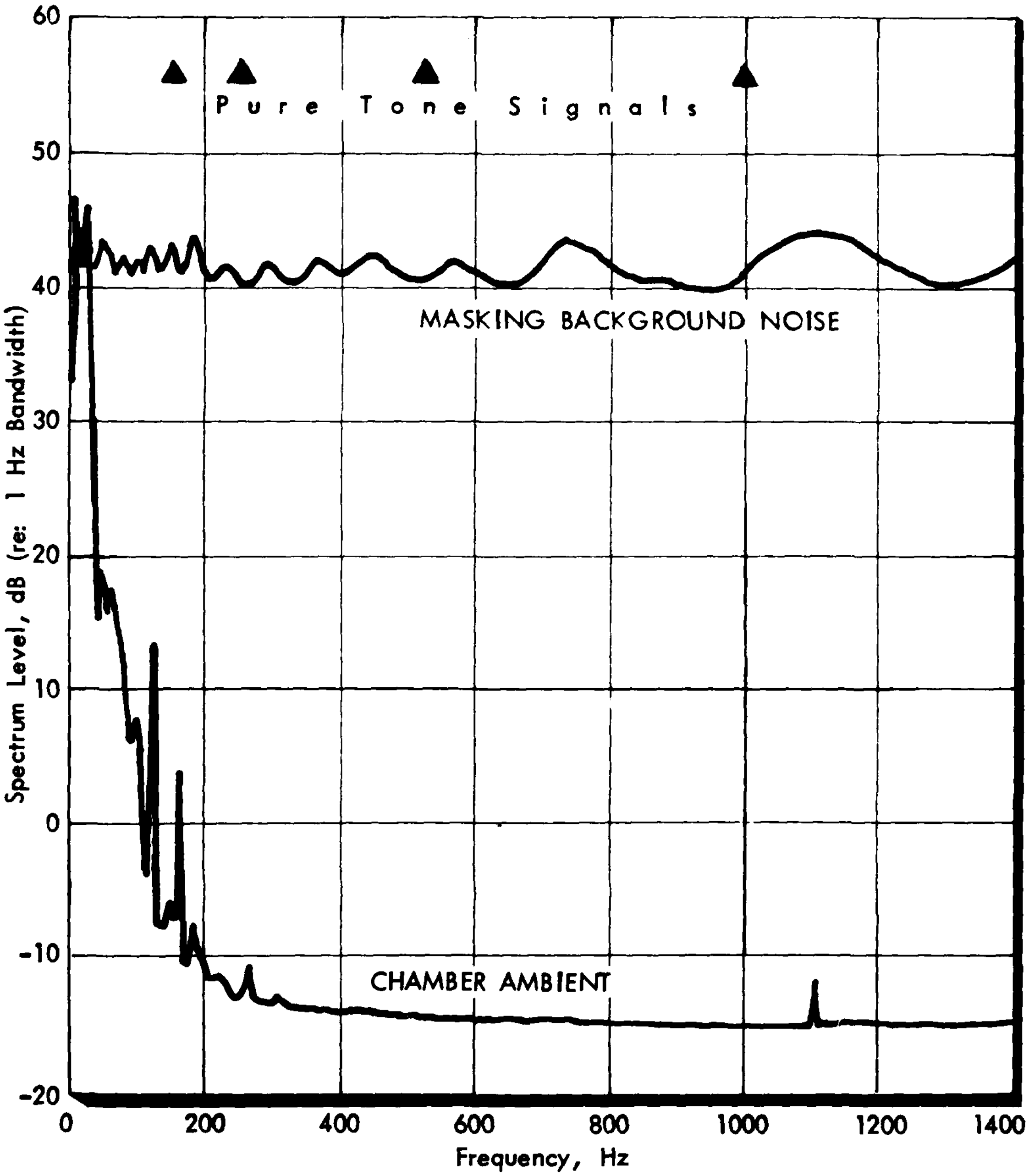


Figure B-3. Spectrum Level of Wideband Masking Noise and Anechoic Chamber Ambient.

Figures B-2 and B-3 show the broadband and narrowband spectra, respectively, with expanded frequency scales. In addition, the spectral content of the ambient noise in the anechoic chamber (in the absence of the laboratory-generated signals) is also shown. The solid triangles indicate the frequencies of the pure tones that were administered to the test participants in each background. Note that the test background noise exceeds the anechoic chamber ambient level by from 40 dB at 40 Hz up to 55 dB at 1000 Hz. Thus, the chamber ambient did not contribute in any significant way to the test conditions.

The tape recorded measurements were subsequently analyzed by the real time audio spectrum analyzer. Long-term root mean square (RMS) values were determined for one-third octave bands from 5 Hz to 2500 Hz. The one-third octave band levels were converted to spectrum level by subtracting 10 log (bandwidth) for each frequency band. These measurements agreed well (within plus or minus 0.7 dB) with those derived from the SD-360. Figures B-4 and B-5 are block diagrams of the apparatus used to generate the acoustic signals in the two experiments.

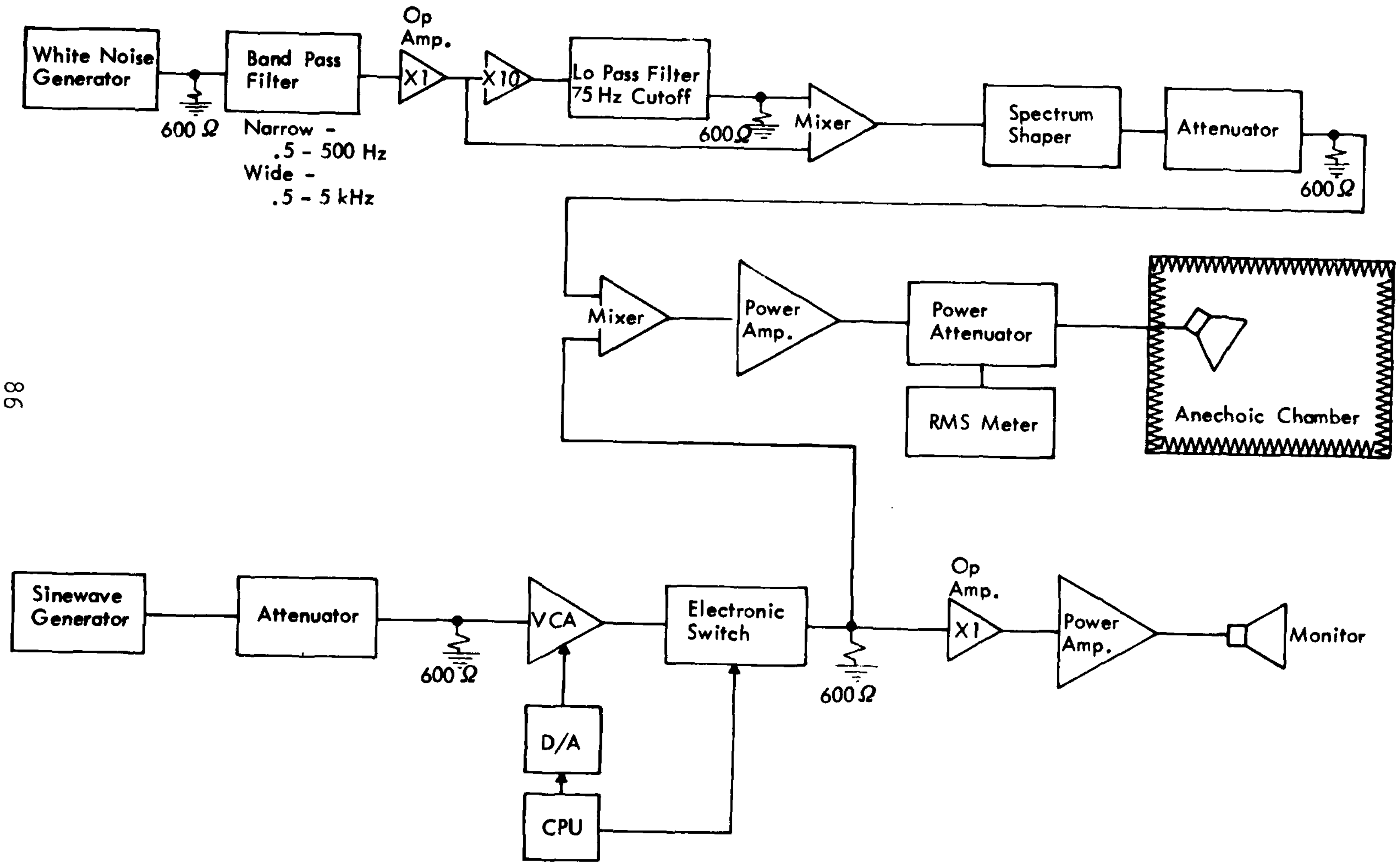


Figure B-4. Block Diagram of Circuitry For Bandwidth Experiment.

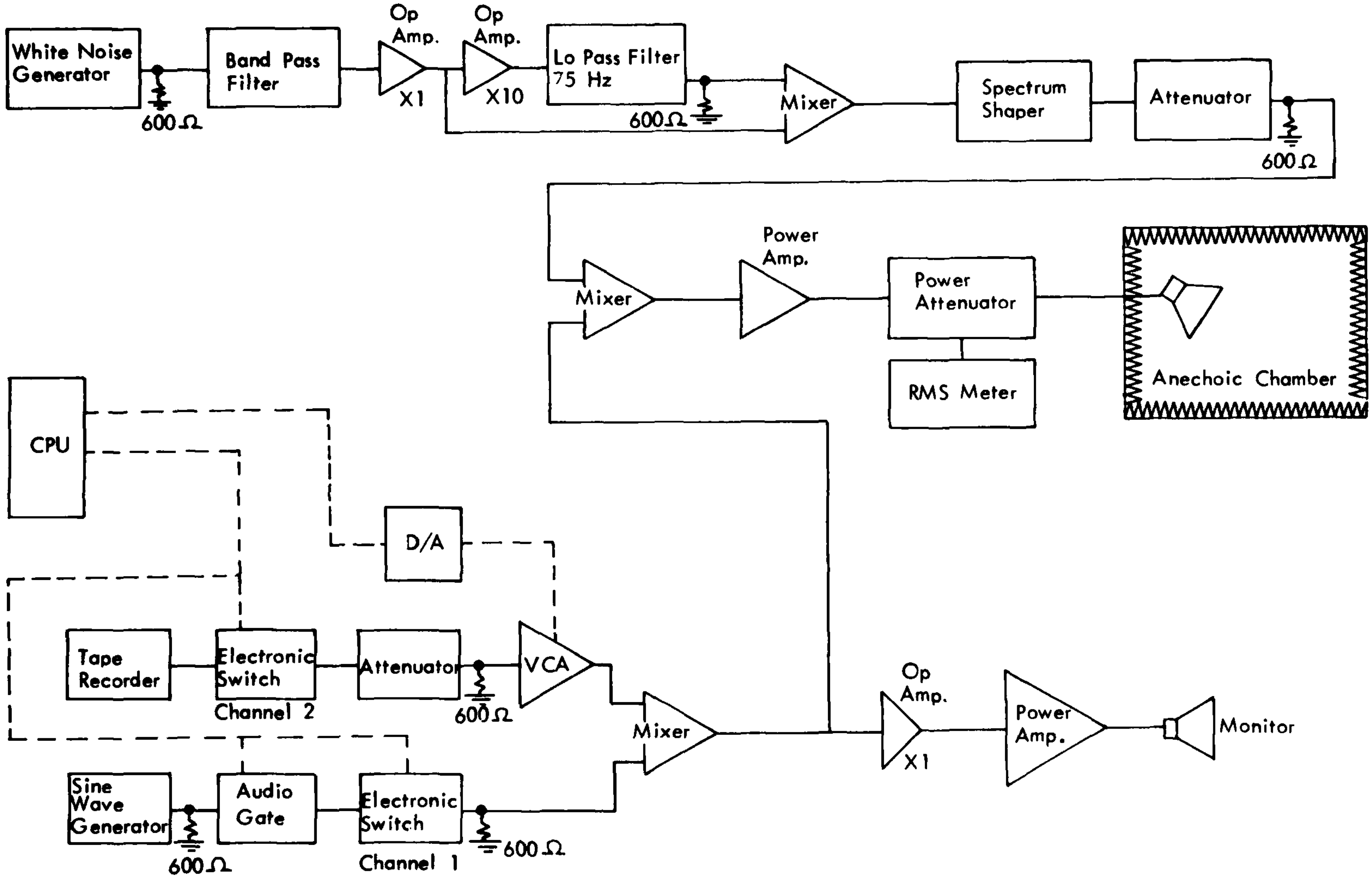


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Figure B-5. Block Diagram of Circuitry For Infrasound Experiment.